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AUG 23 2007
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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In Re Application of:

Mehdi Namazian et al

Serial No.: 10/796,592

Filed: 3/5/04

For: Liquid Fuel Preprocessor

Group Art Unit: 1764

Examiner: Singh,Prem C

Declaration Of Inventors Under 37 CFR §1.131

The undersigned Mehdi Namazian, PhD and John T. Kelly, PhD who are the named inventors in United States patent application Serial No.: 10/796,592 (hereinafter referred to as "subject application") declare and state as follows:

CONCEPTION OF THE INVENTIONS

1. We jointly conceived of each of the inventions of process claims 1 to 19 (hereinafter referred to as "the inventions") of the subject application prior to the date of July 10, 2002.

2. The attached Exhibits 1 and 2 are photocopies of sketches bearing notations which we made of the features of certain of the inventions which we conceived. These sketches were made by us prior to the date of July 10, 2002; the date shown on the document of Exhibit 2 has been masked out on the photocopy.

3. The attached Exhibit 3 is a photocopy of a proposal (herein described as "proposal") jointly prepared by us, as a part of our jobs for Altex Technologies, assignee of the subject application, for submission to DARPA (Defense Advanced Research Projects Agency, a US department of defense agency) under the title Logistic Fuel Preprocessor and Reformer for Fuel Cell Applications. This proposal was prepared by us prior to the date of July 10, 2002. The proposal includes a description of all of the inventions of the subject application which we conceived, as stated in ¶1 above. The date shown on the original document of Exhibit 3 has been masked out on the photocopy.

4. Conception of the specific claims of the subject application which we jointly conceived are supported in the Exhibits as follows:

• Support for Claims 1 - 7: Fig. 2 of Exhibit 3 is a two dimensional version of Fig. 1 of the subject application. It includes a) the fractionator, b) desulfurizer - designated OST, or organic sulfur trap, in this figure, while pg. 4, 7th line from the bottom, describes it as the desulfurizer, c) prereformer, e) reformer, and f) burner. The description of Fig. 2 of Exhibit 3 is given on numbered pages 1, 4, and 9 of the proposal. Claim 1 is supported by Exhibit 3, numbered page 1 in the paragraph starting "The clean fuel fractions ..." Numbered pages 4 and 5 of the proposal expand the description of subject matter of claims 1-7. Thus, numbered page 4 in the paragraph beginning "These challenges are addressed ..." describe the subject matter of claim 2 in the first bullet • *micro-Organic Sulfur Trap;* that of claims 1 and 3 in the second bullet; that of claim 5 in the third and fourth bullets • *catalytic pre-reformer* and • *oxygen-assisted steam reformer;* and that of claim 6 in the fifth bullet • *micro-burner.* Claim 4 is supported by the numerous references to adsorption/trapping of sulfur in Exhibit 3, such as at page 2, first line; page 9, graph of the exhibit's Fig. 7; and page 30, last paragraph. Claim 7 is supported by the paragraph at the top of numbered page 8, as well as in the paragraph beginning "The heavy ends ..." on numbered page 9.

The above claims 1-7 are also supported by the chart on numbered page 6 of Exhibit 3 (identified as "Exhibit 4" on that page), which is the same as of Fig. 6 of the subject application. Also, Figure 5 on page 6 of Exhibit 3 is the same as Fig. 5 of the application. Further, the drawings on the center left and right sides of numbered page 8 of Exhibit 3 are substantially the same as Figs. 2 and 3, respectively of the subject application. And Fig. 8 on numbered pg. 10 of Exhibit 3 is the same as Fig. 4 of the subject application.

The attached Exhibit 4 is a photocopy of a presentation titled Logistic Fuel Preprocessor and Reformer for Fuel Cell Applications given by the undersigned John Kelly et. al. at a DARPA meeting on a date prior to the date of July 10, 2002. The meeting date is masked out on the photocopy. The flow chart on the fifth page shows substantially the same chart as Fig. 7 of the subject application.

• Support for Claims 8-19 The attached Exhibit 5 is a hand-drawn sketch which describes the inventions of numbered claims 8-18 of the subject application. This sketch was made by

us on a date prior to the date of July 10, 2002. The date on the document is masked out on the photocopy.

• Claims 8, 9, 10, 11, and 13 are further supported by the attached Exhibit 6 which is a proposal titled Fuel Preprocessor (FPP) for a Solid Oxide Fuel Cell Auxiliary Power Unit to the Department of Energy (DOE). It was prepared by the undersigned Mehdi Namazian prior to the date of July 10, 2002. The proposal date is masked out on the photocopy. The fuel fractionator step of claim 8 is described on numbered page 2 at the top of section 1.2; the heat exchange step of claim 9 is shown and referenced in Fig. 1 on that page; the burner step of claim 10 is also shown in that figure and described at the end of section 1.2; and claim 11 is supported by numbered page 4 in the third paragraph beginning "It should be noted .." where OST technology is proposed as being incorporated.

• Claim 13 is supported by sketch of Exhibit 5 which shows the desulfurizer step.

• Claim 12 regarding desulfurization by adsorption and sorption is supported by Exhibit 3, especially at numbered page 9 beginning in the last paragraph beginning "The light fraction enters the Organic Sulfur Trap (OST) ..."

• Claim 14-is supported by Exhibit 3, center of numbered page 4 in the third and fourth bullets describing the catalytic pre-reformer and the oxygen-assisted steam reformer.

• Claim 15 is supported by Exhibit 3, center of numbered page 4 in the fifth bullet describing the step of burning the heavy ends to provide heat in the reforming step.

• Claim 16 is supported by Exhibit 3, center of numbered page 4 in the in the third and fourth bullets describing the catalytic pre-reformer and the oxygen-assisted steam reformer.

• Claim 17 is supported by the inventor's descriptions of the fractionation steps in the paragraph beginning "The initial fractionation step is ..." on numbered page 1 of Exhibit 3..

• Claim 18 is supported by the disclosure of use of the light fractionate or "light ends" in Exhibit 6, from the top of page 2 through the second full paragraph on numbered page 3.

• Claim 19 is supported by Exhibit 3 in the paragraph at the top of numbered page 8 regarding wicking the fuel to a heated surface.

SUCCESSFUL TESTING OF THE INVENTIONS SUPPORTING ACTUAL REDUCTION TO PRACTICE

5. The processes of each of the claims 1 through 19 of the subject application were jointly tested by us prior to the date of July 10, 2002. Such testing comprised running a series of tests with apparatus which performed the processes of each of claims 1-19. The conditions of each test duplicated the conditions of actual use. The results of each of those tests were successful in that each process that was tested operated in accordance with their intended purposes. Certain of those results were reported in the first full paragraph of Exhibit 6, page 3, particularly in the sentences "So far, the testing and analysis work performed under this program has proven the feasibility of the fractionator" and ".. tests to date demonstrate that the fractionated diesel is a better quality fuel than the parent diesel."

6. The following documents evidence further support the successful results of tests of the processes of the inventions which were run and recorded by us prior to July 10, 2002:

- Exhibit 7 which records bench-scale performance of the fractionator component of the inventions. The document records that the "fractionator performance is excellent."
- Exhibit 8 which records the adsorption profile of the feed in the tests and concludes that "the adsorbent capacity has been improved by a factor of two."
- Exhibits 9 and 10 which record the fuel desulfurization results from the tests; both exhibits show that the desulfurizer component adsorbs sulfur as intended by the invention. Exhibit 9 shows the speciated sulfur reduction while Exhibit 10 shows the total sulfur reduction.
- Exhibit 11 (which is a copy of page 27 from a report to DARPA) shows results for the reformulation of clean fuel from the fractionator process of claim 5. The results shown in this exhibit are from tests run prior to July 10, 2002 but in which the report is dated for the period from prior to that date up to Aug. 31, 2002. The page refers to the chart of the report's Fig. 21 as showing that "nearly complete conversion of model jet fuel is achieved," which was as intended for our inventions.
- Exhibit 12 (which is page 30 from the report mentioned in the preceding paragraph) shows the test results from the processes of the invention on the effects of catalyst and reactor temperatures on reformulation conversion. The page refers to the chart of the report's Fig. 23 as showing that the target metric (of the reforming) can be met, which was as intended for our inventions.

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Title 18, United States Code, §1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

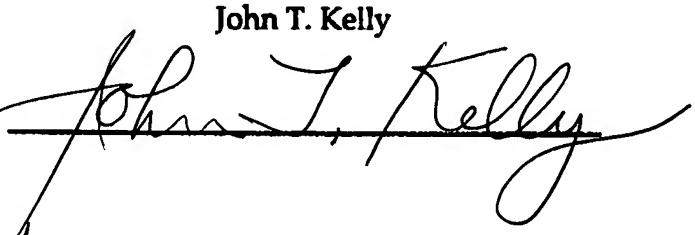
Full name of inventor: Mehdi Namazian

Signature:

Date: August 14, 2007

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Title 18, United States Code, §1001 and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full name of inventor: John T. Kelly

Signature: 

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OIPE
AUG 23 2007
PATENT & TRADEMARK OFFICE
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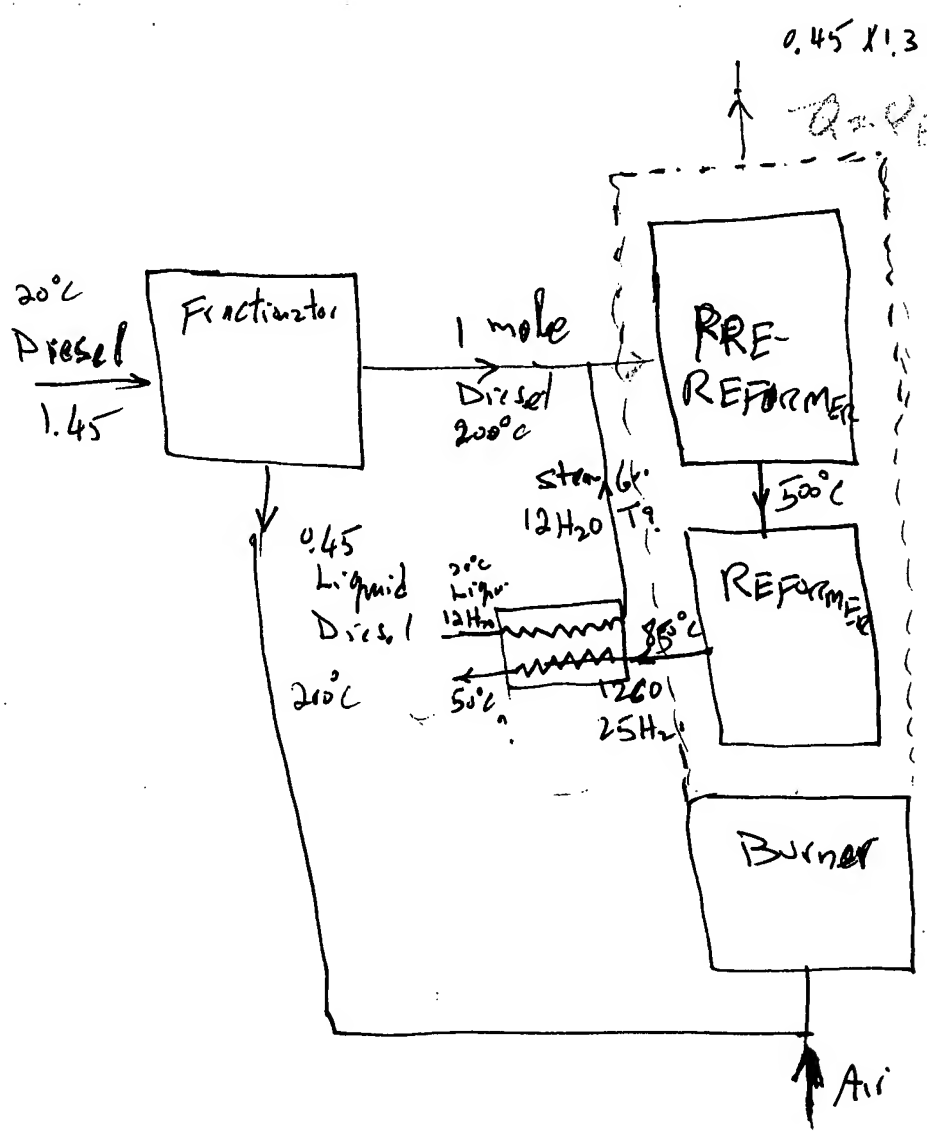


RReformer ✓

$C_{12}H_{26} + 12H_2O \rightarrow 12CO + 25H_2$

$Q_{rxn} = 2455$

Burner

$C_{12}H_{26} + 18.5(O_2 + 3.76N_2) \rightarrow$

$12CO_2 + 13H_2O +$

$18.5(3.76N_2)$

$0.45 \times 18.5 \times 1.3 (O_2 + 3.76N_2)$

Exhibit 1

Fuel Pre-processor and REformer (PPPR) Proprietary AHLA

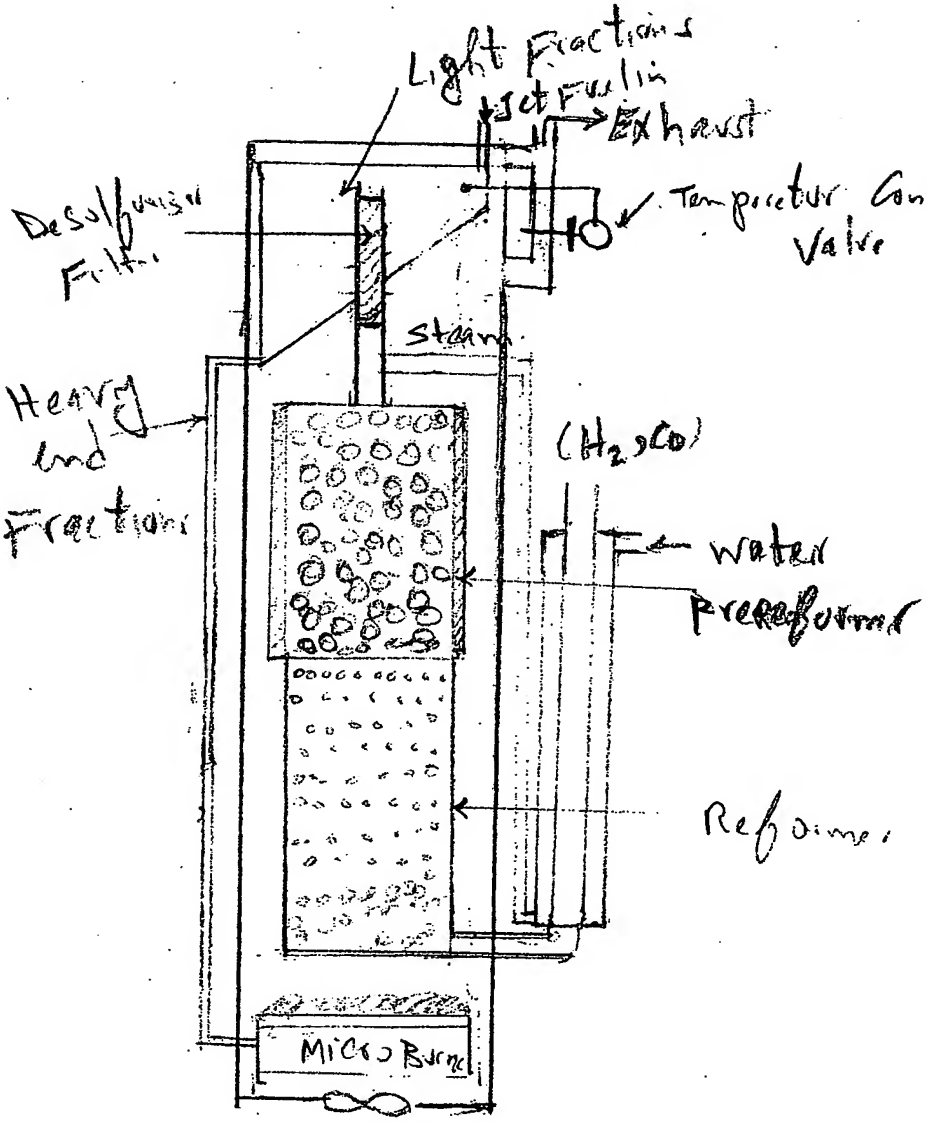


Exhibit 2

DARPA BAA 01-18
Palm Power (PP)

Control Number [ ] for DARPA use only

Performers

Lead Organization Altex Tecnologies Corp. Proposal Date

Volume 1 Technical Proposal [X] please indicate volume number with a check - ✓ Volume 2 Cost Proposal [ ]

Subcontractor/Team Members
Penn State University
Compatible Manufacturing, Inc.

Proposal Title
Logistic Fuel Preprocessor and Reformer for Fuel Cell Applications

Keywords (5 words)
Reformer; JP8; Preprocessor; Fuel; Cell

Technical Abstract

JP8 fuel needs to be processed and reformed to be compatible with fuel cells. Altex's Logistic Fuel Preprocessor and Reformer (LFPPR) innovation can reliably transform JP8 into a clean fuel that can be directly uitlized in fuel cells. When applied to a SOFC fuel cell, the LFPPR will meet the 3 and 10 day Palm Power mission goals. Most importantly, the LFPPR will provide long term reliable operation of the Palm Power system on JP8 and like fuel.

Technical POC	Administrative POC
Last Name: Namazian	Last Name: Kelly
Salutation: Dr. First Name: Mehdi	Salutation: Dr. First Name: John
Street Address: Altex Technologies Corp. 650 Nuttman Rd., No. 114	Street Address: Altex Technologies Corp. 650 Nuttman Rd., No. 114
City: Santa Clara	City: Santa Clara
State: CA Zip: 95054	State: CA Zip: 95054
Telephone: (408) 982-2303 Fax: (408) 980-8611	Telephone: (408) 982-2302 Fax: (408) 980-8611
E-mail: mehdi@altextech.com	E-mail: john@altextech.com

Cost Summary

Total Duration (Months)	Total $ Cost	Total Cost to Government	1st Year $ Cost to Government
36	$2,608,959	$2,493,529	$ 754,459

This Proposal Contains Proprietary Information to Altex

Exhibit 3

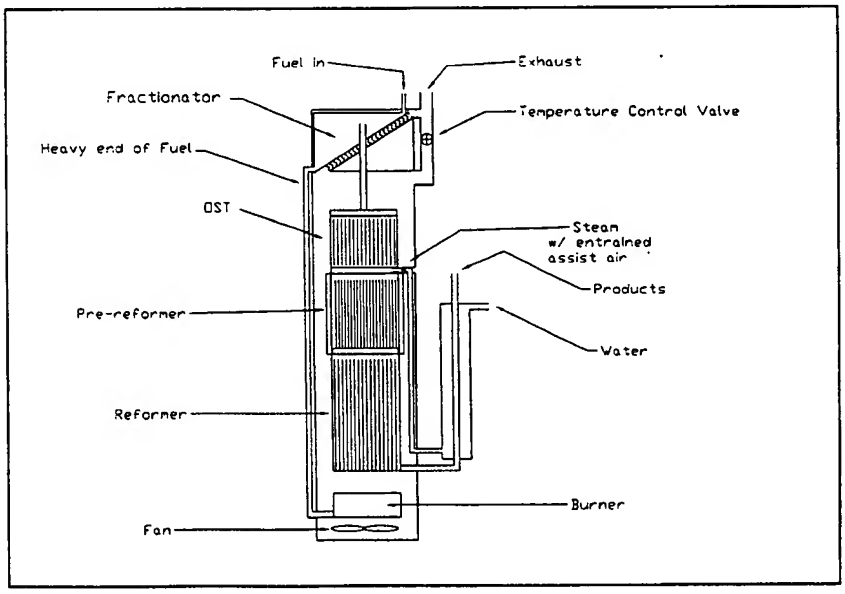
EXECUTIVE SUMMARY

Fuel Cell based power sources are very attractive for Palm Power applications because of their high efficiency. Also, JP8 is very attractive as a fuel to drive power systems because it is safe, easy to transport, readily available and has a high energy density. However, JP8 is a challenging fuel to use in fuel cells because it has heavy ends that can transform into carbon deposits and gums that can block passages and deactivate reactor elements. In addition to the heavy ends problem, JP8 also contains sulfur compounds and inorganic contaminants that can poison fuel cell reactor elements. Therefore, the great promise of fuel cells operating on JP8 is constrained by heavy ends and contaminants in JP8. While these challenges are well known for large fuel cell systems, for Palm Power system scales, the JP8 related challenges become even more severe.

Recognizing the challenges of utilizing JP8 in Palm Power fuel cell systems, Altex has teamed with Penn State University (PSU) to develop and test the innovative Logistic Fuel PreProcessor and Reformer (LFPPR) that will transform JP8 into a clean fuel for driving Palm Power fuel cell systems. Given the great challenge of JP8, the LFPPR incorporates several sequential steps to ultimately eliminate the risk of deposition and deactivation within the small fuel cell stack. By substantially reducing risk at each step, success is ensured. The below figure illustrates the general construction of the LFPPR. Starting from the top of the unit, the LFPPR system includes:

- A fuel fractionator that separates the fuel into light (C8-C13 type molecules) and heavy end (C14-C17 type molecules)fractions
- A micro-organic sulfur-trap (OST)
- An air-assisted steam catalytic pre-reformer for breaking down the C8-C13 type hydrocarbon molecules into smaller molecules,
- An air-assisted steam reformer to reform the smaller molecules to H_2 and CO
- A micro-burner that burns the heavy end C14-C17 molecules to provide the heat needed for the reforming process

The initial fractionation step is critical in that it separates out the problematic heavy ends and inorganic contaminants in the fuel and transports only light clean fuel to the desulfurization and reforming elements. The problematic heavy end components are transported out of the fractionator and to an innovative, small burner that can cleanly burn heavy fuels, over the long term without pluggage. This burner technology has been proven in Altex tests on diesel fuel, which has heavier fuel components then JP8.



The clean fuel fractions exiting the fractionator are than transported into the innovative desulfurization, pre-reforming and reforming steps that clean and transform the fuel ahead of the fuel cell stack. The desulfurizer uses a

novel PSU metal adsorbent coated monolith to trap sulfur and avoid the production of noxious H_2S as in conventional desulfurization. This approach will be an advancement of a successful application of the concept to gasoline by PSU. The pre-reformer and reformer steps will use an innovative PSU air assist feature with steam on catalyst coated ultra-thin wall monoliths, to further minimize the risk of carbon deposit formation. In addition, by breaking reforming into lower temperature pre-reforming and higher temperature reforming steps, carbon formation should be eliminated. This low risk approach is supported by extensive fuel reforming work carried out in recent years by the PSU group.

Besides being clean, the fuel gas exiting the LFPPR is also at a similar temperature to that needed for Solid Oxide Fuel Cell (SOFC) systems. This characteristic, plus the burner and steam reforming approach leads to a highly efficient system. Preliminary calculations indicate that the LFPPR will be 2.5 cm in diameter, 6 cm long, weigh 80 gr and provide 38% to 45% overall fuel to electricity conversion efficiency on JP8. This efficiency is 25% to 27% higher than that projected for Autothermal Reformer. Most importantly, the LFPPR provides long term and reliable operation when using JP8 and like logistics fuel. This is a critical advantage of the LFPPR.

To ensure the successful development and test of the LFPPR, Altex has teamed with PSU, utilizing staff and facilities at their Applied Catalysis in Energy Laboratory and Energy Institute. In addition, to ensure that the LFPPR is designed and manufactured to be a viable product, we have included a small-scale precision prototype fabricator, Compatible Manufacturing, Inc., in the team. These organizations have all of the capabilities needed to successfully develop and test a LFPPR.

Given the promise of the LFPPR, a Phase I program of work is proposed to develop and test a prototype of the system and then fabricate a preproduction prototype that will be integrated with a Solid Oxide Fuel Cell (SOFC) and tested as an integrated 20w electrical power system. Presently, the optimal SOFC contractor has not been selected. At the initiation of the Phase I effort, DARPA and the project team will meet and Palm Power successful SOFC candidates will be reviewed and evaluated for teaming. DARPA will then select the optimal SOFC contractor for joining the proposed team. The SOFC contractor will contribute to the effort throughout the proposed project and, most importantly, will provide a 20w electric SOFC to the team in the final year of the effort for integration and testing as a complete system.

Leading up to the preproduction prototype integrated system test, Altex, PSU, Compatible Manufacturing and the SOFC contractor will develop prototype components and test these components in parallel. Existing models and test systems at Altex and PSU will be beneficially used in these efforts. Following component tests, a fully integrated prototype system test will take place at Altex, including a long term operation test. This will be followed by design, fabrication, integration and test of the preproduction prototype integrated 20w electric system. System tests are expected to take place at both Altex and the SOFC contractor.

At the conclusion of the Phase I effort, an LFPPR and SOFC integrated system, that meets Palm Power goals, will be fully demonstrated. This will position the technology for extensive field tests under the Phase II effort. Success of the Phase I development and test will be assured by the heavy fuels combustion expertise of Altex and the logistic fuel reforming expertise of PSU.

1.0 INTRODUCTION

High energy content fuels and efficient systems are required to meet the Palm Power specific energy targets. This is demonstrated in Figure 1a and 1b, that respectively, show the allowable hardware weight (AHW) of systems operating on JP-8 and methanol. The 3hr, 3 day and 10 day missions are presented. As shown, for both fuels, the AHW for the 3hr mission is small[1] [1]. For the 3 and 10 day missions, the AHW is more substantial for JP-8 than for methanol. In fact, the 10 day mission is impossible with methanol, since it requires unattainable efficiencies. For the 3-day mission, the methanol operating system has to be less than 200 gr and more than 45% efficient. This is extremely difficult to achieve. In contrast, the AHW with JP-8, although challenging, is more reasonable. From these results, it is clear that the higher energy content JP8 fuel is a better choice for Palm Power applications.

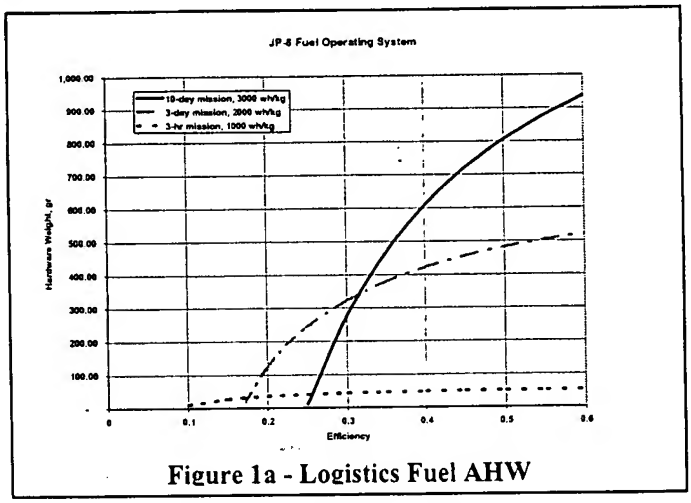


Figure 1a - Logistics Fuel AHW

Figure 1a data also demonstrate that overall efficiency has to be very high and weight very low to meet Palm Power goals, even with JP8. Currently only fuel cells, not limited by Carnot efficiency, have the capability to achieve this level of efficiency. Therefore, they are the obvious choice for Palm Power applications.

Fuel cells operating on hydrogen can achieve up to 56% efficiency. However, hydrogen, and any other gaseous fuel, require heavy and bulky tanks that cannot meet the Palm Power high specific energy[2]. In addition hydrogen has a much greater storage safety risk [2]. Therefore, processing a high energy content liquid fuel for fuel cell applications is the best choice for Palm Power applications.

Considering that JP-8 is readily available at DOD facilities, is easily transportable and safe, it is the fuel of choice for DOD applications. However, there are challenges in reforming logistic fuels for fuel cell use, that require innovative approaches to resolve.

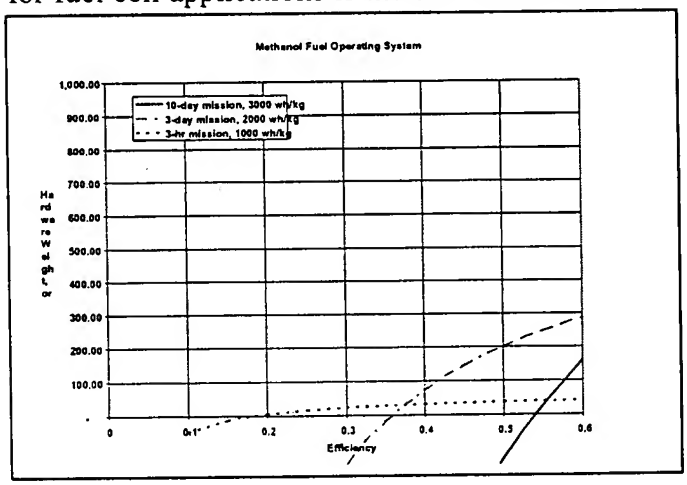


Figure 1b - Menthonal Fuel AHW

Several major challenges for the development of portable fuel cell systems using JP-8 fuel are:

- How to remove the sulfur evolved from the fuel that is at a high enough level to poison most reforming catalysts and fuel cells without producing poisonous and obnoxious H_2S

[1] Efficiency is not critical for the 3-hr mission, and therefore, a direct methanol fuel cell may be the best choice for this application.

[2] A 2 liter steel hydrogen tank, only has 470 wh/kg energy density [Page 217 Larminine and Dicks]. The 50 watts Ball System has less than 500 whr/kg specific energy.

- How to eliminate the problem of carbon formation during reforming from >C8 hydrocarbons in JP-8 fuel, since carbon formation is a serious concern for this fuel
- How to accomplish the sulfur removal and reformulation of JP-8 fuel in a compact processor that can be used in combination with a suitable fuel cell for Palm Power applications
- How to take advantage of such fuel reformulation with fuel cells without the requirement of further quenching and three additional fuel processing steps for CO conversion and removal at lower temperatures (such water gas shift in two stages and CO oxidation)
- How to accomplish the above and maintain the high efficiency to meet the targeted specific energies

These challenges are addressed and overcome in the proposed innovative Logistic Fuel Pre-processor and Reformer (LFPPR). A schematic of this micro reformer is shown in Figure 2. LFPPR is projected to weight 80 gr. and have an 85% fuel conversion efficiency. These are attractive features

The LFPPR consists of:

- A micro-Organic Sulfur-Trap (OST)
- A fuel fractionator that separates the fuel into light C8-C13, and heavy end C14-C17 fractions
- A catalytic pre-reformer for breaking down the C8-C13 hydrocarbons into smaller molecules
- An oxygen-assisted steam reformer in an ultra-thin-wall-monolith (UTWM)-based cellular reactor to reform the smaller fuel molecules
- A micro-burner that burns the heavy ends C14-C17 molecules to provide the heat needed for the reforming

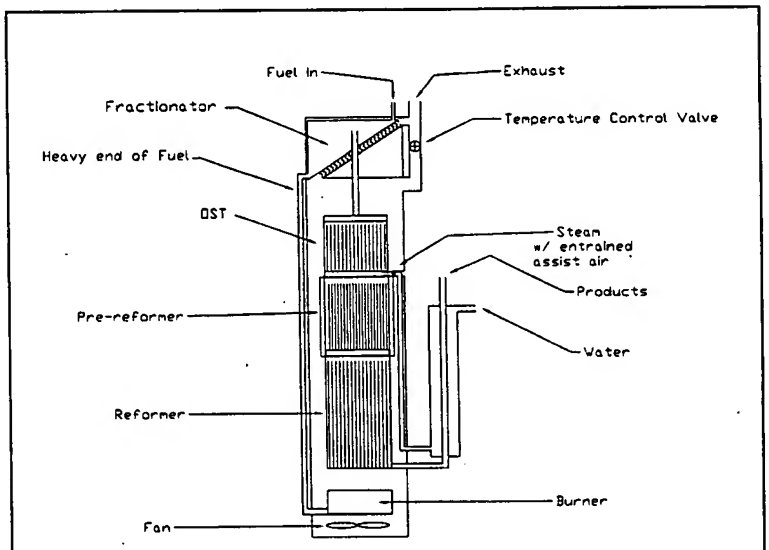


Figure 2 - LFPPR Microreformer

In the LFPPR system, the problematic heavy ends in JP8 fuel are separated from the light components in the fuel fractionator. The heavy ends are then transported out of the fractionator and burned in a reliable wick based micro-burner, based on an Altex innovation developed under the Army supported Low Cost Pocket Stove (LCPS) project. This micro-burner provides the heat needed for the reforming. The important fractionation step removes coke producing two ring aromatics and heavier paraffins than n-tridecane. The light fraction then passes through an Organic Sulfur Trap (OST) that consists of sulfur-capturing metal components dispersed on an ultra-thin-wall mini-monolith. When fuel molecules flow through the OST, the sulfur will be removed quickly, but the hydrocarbon fuel molecules remain unaltered. This innovation has been developed and demonstrated with gasoline at Penn State University (PSU). With the OST, desulfurization of the JP-8 can be accomplished in a compact, replaceable cartridge that can be

regenerated and reused if necessary. In addition, the OST does not produce any H_2S that will be offensive to soldiers.

The desulfurized gas is then upgraded in an oxygen assisted pre-reforming step, that cleaves C-C bonds in C8-C13 hydrocarbons. Pre-reforming is a common procedure in the reforming industry and, since it is performed at relatively low temperature (400-500C), it drastically reduces the risk of carbon formation [1]. This step breaks-down most of the C8-C13 hydrocarbons to C1 to C2 molecules plus CO and H_2. This upgraded gas is then fully reformed in the oxygen assisted steam reformer step, operating at 800C to produce reformate (H_2, CO, H_2O) needed for the fuel cell. The risk of carbon deposition in this step is low, since most of the gas consists of C1 and C2s. This risk is further reduced by the presence of oxygen.

The proposed oxygen-assisted reforming takes advantage of PSU [3, 4] and O'Conner findings [5] that adding a very small amount of oxygen, as air, greatly minimizes carbon formation on the catalyst surface during steam reforming. Only a small amount of O2 (3% vol) is sufficient, which makes this process nearly as efficient as steam reforming. This is different from auto-thermal reforming, where more than 30% oxygen is added. As a result the oxygen assist steam reforming has higher H_2 production efficiency than auto-thermal reforming [6].

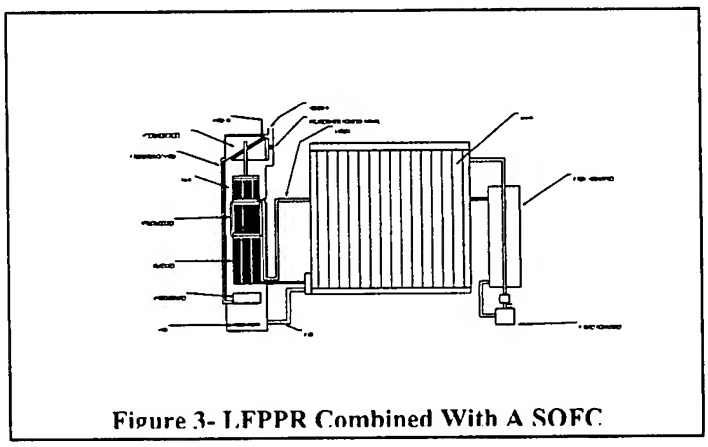


Figure 3- LFPPR Combined With A SOFC

OST, pre-reformer and reformer elements will be constructed of monolith substrates that have the same diameter, so they can easily stack up as the micro-fuel processor, as illustrated in Figure 2. The system will utilize ultra-thin-wall monoliths, that have recently become available commercially, to construct cellular micro-catalytic reactors that allow fast mass and heat transfer, without the need for pressurized operation.

LFPPR is fuel flexible, and can be adapted to use other logistic fuels with minimal design changes. This flexibility is made possible, by the fractionator, that will always fractionate the fuels at a preset carbon number, (e.g. C13) to avoid downstream carbon formation. Even if diesel fuel is used, only light fractions below C13 will be sent to the reformer. The heavier ends will be burned in the micro-burner. This is an extremely useful flexibility for the military, when emergency situations may force operators to use fuels other than JP8. This flexibility will also compensate for the variations that may exist among JP8 fuels, coming from different refineries or regions.

Such a micro-fuel processor can be used directly in combination with a micro-solid-oxide fuel cell for Palm Power applications. Figure 3 shows the LFPPR micro reformer integrated with an SOFC, the first application chosen for this Phase I effort. The projected weight and efficiency of the combined system are 400 gr and 42%, meeting both the 3-day and 10 day mission requirements. Since the SOFC operates at high temperatures, its use may not appear to be advantageous in terms of the need for heat insulation when used as portable power source. However, recent advances in materials has resulted in commercially available insulating metal foils and other light-weight insulation. As a result, fuel cell manufacturers and research and development organizations are now designing micro-solid oxide fuel cells [7]. These fuel cells

also operate at lower temperatures (800C) than industrial scale SOFCs. This allows using metallic bipolar plates and lower cost manufacturing techniques, and also reduces thermal stress, increases durability, reduces startup time, and increases efficiency. Note that both the SOFC and LFPPR operate at 800 C, making them thermally compatible.

It should be noted that external reforming is a lower risk approach with SOFCs operating on logistic fuels. Current research and development for solid oxide fuel cells for commercial applications generally involve fuel pre-reformer and either an external reformer or internal reformer [1]. Some recent advances in laboratory research has made it possible to make a solid oxide fuel cell for direct electro-chemical oxidation of light hydrocarbons, such as methane and ethane [8]. However, it is widely known that the use of heavy hydrocarbons of > C4 can cause significant deactivation and coking problems associated with most anode catalysts utilized in SOFC [1].

2.0 BACKGROUND ON LOGISTIC FUELS AND LFPPR CONCEPT

Before describing the LFPPR in more detail, some background is given on the challenges of reforming logistic fuels.

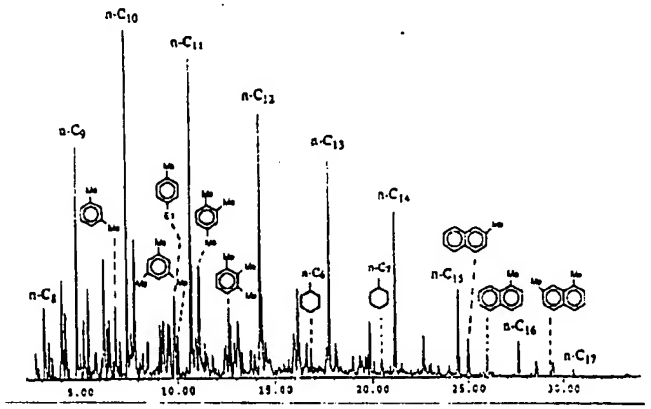


Figure 4 - Structure of JP8

2.1. LOGISTIC FUEL CHALLENGES AND SOLUTIONS

JP8 and diesel fuels are a mixture of hydrocarbon compounds – paraffins, olefins, napthenes, and aromatics - with boiling points ranging from approximately 150C-300C and 175C-400C, respectively. There are also secondary compounds, containing sulfur, nitrogen and oxygen. The military logistic fuels, such as JP8 and diesel fuels, contain up to 2000 ppm sulfur. Deep desulfurization of such fuels is necessary for most fuel cells, although high-temperature fuel cells, such as solid-oxide fuel cells, are more resistant to sulfur (tolerant to sulfur at a few ppm level) than low-temperature fuel cells, such as proton-exchange-membrane fuel cells (tolerant to sulfur at < 30 ppb level). Established approaches for removing sulfur are only suitable for large, fixed site, power plants, but not for mobile power applications. They need hydrogen, they are bulky and produce H_2S, that needs to be absorbed, to avoid obnoxious odors. In addition, catalysts used in these systems are not compatible with the high level of sulfur and other compounds that are present in logistic fuels. The need for new approaches for desulfurization of logistic fuels has been highlighted by Dr. James Stephens of US Army Power Division at the Army Research

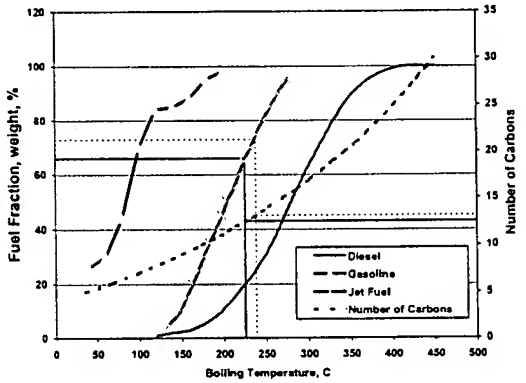


Figure 5 - Fuel Boiling Point Fraction and Number of Carbon Atom Comparisons

Office Workshop on Fuel Processors, held during June 19-21, 2000 at the University of Michigan.

The other issue that needs to be addressed is the coking tendency of logistic fuels. This tendency makes reforming of these fuels difficult. This difficulty has been reported by Eltron [9] and McDermot [10]. While, the logistic fuel reforming carbon deposition problem has not been extensively researched, fundamental work that has been done in the fuel refining industry shows that as the boiling point of the fuel increases, so does its coking tendency. This increased carbon deposit tendency is attributed to increasing number of carbon atoms in the fuel molecule, and the emergence of multi ring aromatics with increasing boiling point temperatures. Figure 4 shows a GC-m.s Chromatogram of JP8, performed at the PSU laboratory [11]. As shown, the two ring aromatics start emerging after C14. Table 1 shows the boiling points corresponding to these two ring aromatics. As shown, these compounds emerge at the 240 C boiling point. This indicates that fractionating the JP8 at 240 C will remove the two ring aromatic compounds and thus substantially reduce the carbon deposit tendency of this fuel.

Figure 5 presents the boiling point ranges of gasoline, JP8 and diesel fuel. Over laid on this plot is a line giving the number of carbon atoms per fuel molecule. As shown, over 75% of the JP8 fuel fraction is below the 240 C boiling point. By fractionating the fuel at 240 C, not only are the two ring aromatics removed, but the heavy ends, C14-C17, are also eliminated. As discussed later, to generate the heat required for reforming, 34% of the fuel must be burned. This requires fractionating the fuel at 225 C, which eliminates C12-C17, as shown in Figure 5. By eliminating all molecules C12 or greater from the reformer feed, carbon desposition potential is greatly decreased.

Table 1- Two Ring Aromatics in JP-8

Component	Boiling Point, C
2-Methylnaphthalene	241.4
1-Methylnaphthalene	244.7
2,6-Dimethylnaphthalene	262
2,3-Dimethy;naphthalene	269

As shown in Figure 5, the gasoline boiling point range is between 50C-200C. This range overlaps with the JP-8 lighter fractions. This comparison demonstrates that, as the JP8 maximum boiling point component is reduced by fractionation, the work that has been accomplished on reforming gasoline will become useful in designing the catalysts for the fractionated diesel fuel.

From the above, it is clear that by removing the heavy ends, the risk of carbon deposition is drastically reduced. To reduce the risk even further, a pre-reformer is included in the LFPPR. Pre-reforming is common in the steam reforming industry, and is used to convert high molecular weight hydrocarbons, via steam reforming, at relatively low temperature[1].

There is considerable data on the effect of temperature on carbon deposition. The rate is reduced drastically at lower temperatures, for the same molecular weight fuel. The need to include a pre-reforming step for JP8 is based on work at Penn State. The group at Penn State has performed detailed chemical analysis of many JP8 type logistic fuels produced from different manufacturers and from different feedstocks [11, 12]. They have demonstrated that JP8 type fuels can undergo thermal decomposition to form carbonaceous solid deposits both in batch reactors [13, 14, 15] and in flow reactors in time scales on the order of seconds [16, 17]. This risk is reduced with addition of pre-reformer step, as used in the LFPPR.

To have an efficient system, the heavy ends that are filtered out of the JP-8 need to be burned. For the LFPPR, a 20W micro-burner is required. Burning logistic fuels in small systems is challenging. The heavy ends can coke and create carbonaceous residues as they are heated

ahead of combustion and broken down in the combustion process. Deposits then plug the small passages that are required to burn this fuel in conventional burners at small scale. This pluggage issue has been addressed in a burner developed by Altex for the Army. The need for small passages was eliminated by developing a Porous Surface Element (PSE) special wick, that pumps and vaporizes the logistic fuels without plugging. The wick was packaged in a special small burner called the Altex Pocket Burner (APB). This burner makes use of the PSE wick system and burner screens to produce heat outputs from approximately 1500w down to 50w. To date, tests have proven operation at scales of 600w, 300w and 50w. Through cycle testing, the burner has been shown to produce a stable output over 500 cycles of on-steady-off operation and 120 hours of steady operation. It is expected that the burner could be adapted to the Palm Power application. Besides meeting the reliable and consistent long term heating target, the burner consists of only a few simple nonmoving parts. This simplicity promotes light-weight, as well as good reliability.

Figure 6 presents a schematic of a 600w linear version of the APB. While a linear version is illustrated, the burner can be configured into other shapes (oval, rectangular, etc.) to suit a needed application. In fact, through Altex tests and analyses, it has been found that the burner output is proportional to wick length and screen area. Therefore, burner scaling for the Palm Power application is straight-forward.

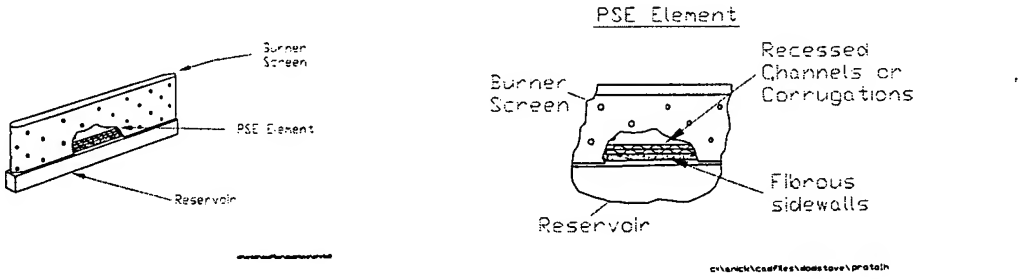


Figure 6(a)Linear APB Burner and (b)PSE Wick Element

As shown in Figure 6a, the APB consists of three main parts; a stamped light sheet metal fuel reservoir, a special Porous Surface Element (PSE) ceramic wick, and perforated screens above the wick, that interact with the flame contained within the screens. The wick has the functions of pumping the fuel to the wick end and receiving heat from the flame to vaporize the liquid fuel. In conventional high pressure feed burners, these functions require many components that add to the system weight. Furthermore, conventional burner components tend to be machined parts that have small passages, that will tend to plug with residues from JP8 fuel. This is avoided with the APB through special

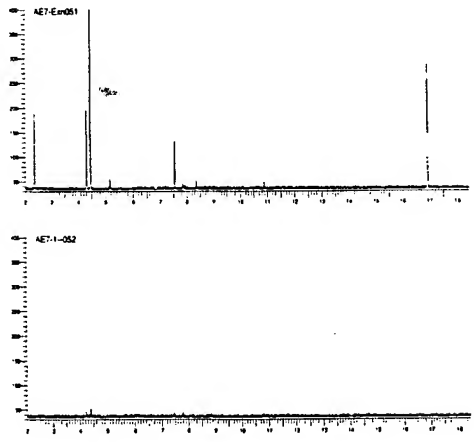


Figure 7. Adsorption desulfurization of a real gasoline fuel sample: GC-FPD chromatograms before (top) and after (bottom) passing through OST. (OST Adsorbent: A-1; Feed: Gasoline-E) [Ma, Sun, and Song, unpublished, PSU, Jan 2001].

features of the PSE.

The PSE element, highlighted in Figure 6b, is configured with multiple vertically aligned passages that have a range of widths. Also, the central area of the wick has recessed vaporization surfaces. The raised thin surfaces are used to start the flame, and typically operate at elevated temperatures. These surfaces can develop some carbon deposits over time, as a result of exposure to the flame. This occurs particularly during shutdown, where the flame approaches the surface. However, the recessed surfaces, where most of the vaporization occurs during steady operation, are removed from high heat fluxes and operate at lower temperature, with much less carbon deposit formation. In addition, passage widths are graded in the wick so that as one class of passages becomes restricted, larger passages take over. With this approach, the burner will provide consistent heat output over the long term, as demonstrated by Altex APB cycle tests, where the AFB operated over 500 cycles and 80 hours of operation with no degradation in output. In contrast, burners that have small orifices or passages or fine porosity wicks for the fuel, will plug within 20 hrs of operation. This burner technology will be used as a base to develop the LFPPR micro burner.

2.2 Logistic Fuel PreProcessor and Reformer System

Figure 2 shows the proposed LFPPR micro reactor. As shown, logistic fuel enters the fractionator at the top of the system. The fuel is either pumped or gravity fed, provided that the fuel source is properly positioned to provide the low pressure required for the system. As the fuel flows over the heated inclined surface, light fuel fractions evaporate, and the heavy ends flow down into the Micro-burner located at the bottom of the unit. The fractionator temperature is set for optimal energy use efficiency and the desired fractionation need. The heat to the fractionator is supplied by hot gases flowing past the finned passage located under the inclined surface. This path is designed to have a higher resistance to the flow than the side exhaust line, located on the right hand side of the unit. When the fractionator temperature exceeds the preset condition, the side exhaust valve opens. This stops the flow from passing under the fractionator, thus maintaining its temperature.

The heavy ends exit the fractionator, and flow down into the micro-burner reservoir. A PSE wick, not shown, draws the fuel to the heated end, where it is vaporized and burns with the incoming air supplied by a fan. As discussed in Section 2.1 this micro-burner will be developed based on the APB burner, that has been proven to work reliably on jet and diesel fuels from –30 C, to 50 C.

The light fraction fuel enters the Organic Sulfur Trap (OST). The OST consists of sulfur-capturing metal components dispersed on an ultra-thin-wall mini-monolith, that effectively captures the sulfur and allows the hydrocarbons to pass through unaltered. The basic concept of the OST is the selective interaction between certain metal components and sulfur compounds in the presence of hydrocarbon fuels. The concept has been developed at PSU and tested on a commercially available gasoline sample. The GC-FPD chromatograms in Figure 7 shows the sulfur compounds in the gasoline before (top in Figure 7) and after (bottom in Figure 7) passing through the OST (OST test A-1). As can be seen from Figure 7, the OST has been effective on gasoline. For LFPPR, the adsorbent materials will be tailor-designed specifically for JP8 fuels. The gas exiting the OST, that is now sulfur free, enters a mixing chamber located between the OST and pre-reformer. Steam, and a small amount of air, induced by the steam flow, enters this chamber. Fuel, steam and air mix and enter the pre-reformer, to provide a steam to carbon ratio of 3 and maintain a 3% oxygen concentration. The pre-reformer, will consist of Ru and Rh catalysts supported on zirconia. These catalysts are loaded onto an ultra-thin-wall monolith that

has a very high surface area to volume ratio. The pre-reformer will operate at 500C, where the light fractions (C9-C12) are broken down to lighter hydrocarbons, H_2 and CO. By operating at low temperature, and operating with sufficient oxygen, the risk of carbon deposition is minimized.

The pre-reformed gases, now upgraded to a much lighter hydrocarbons mixture, enter the final section to complete the oxygen-assisted steam reforming. As in pre-reforming, steam reforming of light hydrocarbons in the presence of oxygen minimizes the carbon deposition risk. The presence of a small amount of oxygen in the system facilitates the spill-over of oxygen species between CeO_2 or ZrO_2 support and metal sites. This will lead to improved reaction activities while eliminating carbon formation.

Prior research by various research groups, that are summarized in a recent review [18] and reported at a Fuel Cell Seminar in November 2000, provide background and also lend support to the LFPPR concept. In particular, there are several recent reports on catalytic fuel processing by autothermal reforming for automotive applications by Argonne National Laboratory [19, 20], Pacific Northwest National Laboratories [21], Degussa Metals Catalysts Cerdez [22], DaimlerChrysler [23], BWX and McDermott Technology [24]. There are distinct differences between the LFPPR proposed approach and those reported by others. The proposed approach is different from conventional autothermal reforming, where all of the fuel is reformed and a large amount of oxygen is introduced into the reformer to release the needed heat to reach the thermo-neutral state. Oxygen-assist steam reforming, proposed for the LFPPR, only uses 3% O_2. This is only used to reduce carbon deposition tendency. The advantages of steam reforming versus autothermal reforming, in terms of conversion efficiency, are highlighted by analytical evaluations performed by Bloomfield [6]. These results demonstrate that the oxygen assist steam reforming H_2 production efficiency can reach 95%. The corresponding values for auto-thermal reforming and Partial Oxidation (POX) are 82% and 75%, respectively [6]. This study also shows that the excess steam, that may be used in steam reforming, does not result is a large energy loss.

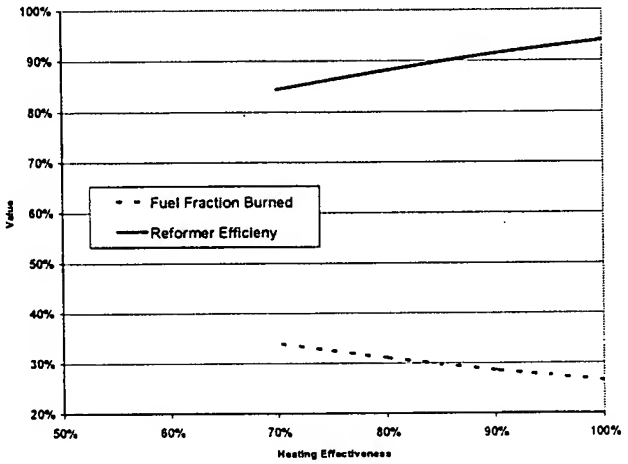


Figure 8 - Reformer Efficiency and Fuel Fraction Burned

The fuel conversion as well as carbon deposition benefits of the LFPPR are highlighted by preliminary system calculations performed by Altex. Figure 8 shows a plot of fuel conversion efficiency calculated using the Altex Thermo-Fluid Model (ATFM). The micro-reactor efficiency is plotted versus the heating effectiveness. The heating effectiveness is reduced by the sum of the micro-burner exhaust loss and the system shell heat loss. The reformer efficiency is defined as the LHV of the product gases divided by the LHV of the fuel used. This plot also shows the fraction of the fuel that is burned for process heat. At 100% heating effectiveness, the system is 93% efficient. This value is reduced, as heating effectiveness decreases. At the expected 80% heating effectiveness, the reformer efficiency is 90%, and 30% of the fuel is burned, leaving 70% to be reformed. Referring to Figure 5, the 70%

of the fuel contains lighter than C13 molecules. Based on an earlier discussion, this meets the low carbon formation potential target. At a more conservative 70% heating effectiveness, the reformer efficiency and the fuel fraction burned and reformed are, 85%, 34%, and 66% respectively. Referring to Figure 5, 66% fuel fraction corresponds to a fractionator temperature of 225C and a carbon number of 12. This exceeds the 240C and C14 targets for the fractionator design.

The high efficiency of the LFPPR and the low carbon formation potential are attractive. Assuming 85% to 90% efficiency range for the LFPPR, 50% to 55% electric conversion efficiency range for the fuel cell, 95% fuel cell fuel conversion efficiency and 95% electrical efficiency, the system efficiency range will be 38% to 45%. In contrast with an Auto Thermal Reformer (ATR) fuel conversion efficiency of 73% [25], the overall FC system efficiency range will be 33% to 36%. Therefore, the LFPPR based system is 25% to 27% higher in overall efficiency than an ATR based system.

Besides promoting good overall power system efficiency performance, the LFPPR is also compact and has a low weight. It is projected that the unit will be 2.5 cm in diameter and 6 cm tall and weigh less than 80 gr. When combined with a SOFC, the system weight will be less than 400 gr. This meets both the 3 and 10 day mission targets.

Based on the above discussion, the proposed LFPPR has a high potential to meet the Palm Power targets. In addition, it achieves the Palm Power targets using logistic fuels, with minimum risk. While the approach has substantial potential, work is required to develop and prove the LFPPR prior to extensive field trials by the military. The proposed five task program of work to accomplish this objective is described below.

3.0 PROGRAM OBJECTIVE

The objective of the proposed effort is to develop and test an integrated Logistic Fuel Pre Processor Reformer (LFPPR) that will have high efficiency, low volume, low weight and operate very reliably on JP8 and like fuels.

4. CONCEPT IMPLEMENTATION PLANS

As described above, the success of a JP8 Fuel Cell (FC) system will critically depend on preprocessing the fuel to a form that is compatible with FC systems that can only operate on clean fuels. Altex in collaboration with Penn State University (PSU) has identified a fuel preprocessing system, called the Logistic Fuel Pre Processor and Reformer (LFPPR) that will be able to process JP8 to a form directly compatible with Solid Oxide Fuel Cell (SOFC) systems of interest to DARPA. In addition, through inclusion of developed process steps for CO removal and deep desulfurization, the LFPPR will be able to process JP8 to a form compatible with even Proton Exchange Membrane (PEM) FCs. However, given the close fit of the LFPPR with SOFCs, this type of FC has been targeted by Altex and PSU as the first application of the LFPPR.

As noted above, the LFPPR has evolved from recent work. Therefore, only a limited amount of time has been available to identify and team with a high potential SOFC contractor. However, an immediate selection of a SOFC contractor is not essential, since the LFPPR can be easily adapted to all SOFC technologies planned to be developed for Palm Power applications. In fact, rather than to select a SOFC contractor now, it is worthwhile to engage DARPA in a review and discussion of which DARPA selected SOFC technology should be integrated with the LFPPR. Also, if of interest to DARPA, the review and discussion can be extended to PEM type technologies as well. By allowing DARPA to participate in SOFC contractor selection, the best FC technology will be chosen for integration with the LFPPR.

Given that a SOFC contractor and development effort are not currently part of the proposed effort, the work fits the compact integrated fuel processor system component category highlighted in the BAA solicitation. However, as described below, the proposed project is planned to cooperate closely with a DARPA selected SOFC contractor over the length of the effort. In the first two years, the LFPPR efforts under the proposed project and SOFC efforts under another proposed project will proceed in parallel to develop the key system components. In the third year, these components will be brought together and tested, both under the LFPPR and SOFC projects. Therefore, while the LFPPR proposed project is initiated as a component focused effort, the end result will be a test of an integrated LFPPR and SOFC power system that meets Palm Power goals. Prior to discussing the project in detail, the proposed project team and their contributions are described.

Table 2 presents the current team members and their expected roles under the project. As shown in the table, Altex is the lead organization in the effort and is responsible for developing and testing the LFPPR. PSU will provide science and technology development for key subsystems in the LFPPR. An important element of this project will be the design and fabrication of a compact integrated fuel processor. To augment Altex's and PSU's technology development expertise, Compatible Manufacturing, Inc. will provide miniaturization and manufacturing expertise to produce an LFPPR that can be translated into a manufactured product, once field demonstrations prove the technology. In Sections 7, 8 and 9, more detailed background is given on team member capabilities.

Table 2- LFPPR Team and Responsibilities

Altex	Technology developer and system integrator. Developer of the fractionator, micro-burner and the integrated system. Program management
Penn State Univ.	Science and technology development for the desulfurizer, pre-reformer and reformer.
Compatible Manufacturing	Rapid prototyping and micro fabrication
SOFC Developer	SOFC technology developer

The proposed project is broken into five key tasks. In Task 1, Altex and PSU will meet with DARPA and review project goals, fuels utilized and FC contractors selected by DARPA. Importantly, under this first task, DARPA will select the FC technology and contractor to be integrated with the LFPPR. Altex and PSU will then meet with the chosen FC contractor to reach an agreement on cooperating together and to produce a plan that will coordinate LFPPR and FC development and test activities over the three year length of the effort.

In Task 2, Altex and PSU, with the inputs of the FC contractor, will design a LFPPR product for an application of interest to DARPA. The FC contractor and DARPA will review and give feedback on the design, that will then be used to refine the design.

In Task 3, the product design will be translated into laboratory prototype test hardware and tests at Altex and PSU will be carried out to prove component performance. In addition, Altex will integrate the prototype components together and test the integrated system at Altex. The FC contractor and DARPA will review results and DARPA will conclude on the viability of the LFPPR approach.

In Task 4, Altex and PSU, in cooperation with the FC contractor, will refine the LFPPR design so that it provides optimal performance when integrated with the selected FC technology. After review and approval of the design by DARPA, the micro-reactor LFPPR system will be

fabricated by Compatible Manufacturing. In preparation for testing, the LFPPR will be integrated with the selected micro FC and then tested in Altex's laboratory. Once Altex testing has been successfully concluded, the system will be shipped to the FC contractor for additional laboratory testing, with a focus on FC issues. Once these tests are successfully completed, the integrated system will then be sent to a DARPA chosen military unit for brief field tests as a simple battery changer.

In Task 5, Altex, PSU and the FC contractor will gather all results from the effort and evaluate the potential of LFPPR and FC to meet Palm Power military applications. Completion of this task will then position the LFPPR and FC technologies to move forward into the Phase II effort. In summary, the proposed project will start with LFPPR component development and proof testing and end with an integrated LFPPR and FC demonstration test, that will fully meet the objective of the Phase I of the Palm Power program. Details of the project tasks are now described.

4.1 Task 1-Application Definition, Fuels Assessment and Selection and Plan Preparation

The purpose of this task is to define the FC and power applications of interest to DARPA, evaluate the range of fuels that the LFPPR will be expected to process, select a FC technology and contractor for integration into this effort and prepare the program plan.

4.1.1 LFPPR Implementation Plan

The purpose of this subtask is to refine the program plan. At the beginning of this effort, team members, including Altex and Penn State will meet with DARPA to discuss and update project goals, technical approach, tasks and schedules. Table 3 presents a list of the preliminary LFPPR goals. During the meeting, these goals will be reviewed and updated, as required, with the concurrence of DARPA. An important function of this meeting will be to review FC technologies and contractors selected by DARPA and, with the help of DARPA, select a FC contractor for integration with the LFPPR project. It is anticipated that the FC technology selected will be a SOFC type system. Once the FC contractor has been selected, Altex will contact and meet with the contractor to plan cooperative activities through the length of the project. Also, the FC contractor will provide inputs that will be used to further refine the specifications given in Table 3.

Table 3 - LFPPR Specifications and Requirements

Fuel	JP-8
Target Cell for Phase I	20 watts SOFC
Product sulfur	Penn
Energy Density (including Fuel cell)	2000 and 3000 wh/kg for 3 and 10 day missions
Weight	80 gr
Startup time	3 minutes
Efficiency	90%
Emission levels	Consistent with appliance requirements
Visible signatures	None
Heat signature	Minimal, to be defined
Durability	Meet established durability standards

The fuel specified for the system is JP-8. This is the lightest logistics fuel. The LFPPR is flexible, and could utilize other logistic fuels, like diesel, as a backup fuel, provided that the fuel is fractionated to a level that it is acceptable to the LFPPR. The current plan is to design the LFPPR to accept fuel compounds with up to C14 carbon atoms. To separate out the heavier compounds, the fractionator needs to operate at 250 C. At this temperature, the fractionator

operating on diesel fuel will send 40% of the fuel to the reformer and the remaining 60% to the micro-burner. This has efficiency and fuel handling implications. These issues will be discussed with DARPA and as needed, the backup fuel option will be included in the LFPPR goals.

Based on updated goals and updated approaches, Altex and PSU will then prepare a project plan, covering tasks, schedules, important milestones, deliverables and detailed budgets for the complete effort. The plan will then be transmitted to DARPA for review and approval. Once approved, the plan will be used to guide the effort.

4.1.2 APPLICATION DEFINITION

The purpose of this subtask is to define the needed LFPPR output conditions for the FC application of interest.

Ideal input conditions for the FC will be defined in consultation with the FC contractor. The first target application of the LFPPR is a 20 watts SOFC. Table 4 shows the projected gas conditions exiting the LFPPR reformer. This gas composition is expected to be well suited for SOFC applications. The temperature of the gas exiting the reformer is 800C.

Table 4 - Reformer output conditions, dry basis

Parameter	Value
H_2	75.4%
CO	24.2%
N_2 and CO_2	0.4%
Sulfur	Free
Temperature out of reformer	800 C

Traditionally SOFC's have been developed for stationary applications, operating at 1000 C. However, for portable applications, lower temperature SOFC's are being developed. The lower temperature allows using metallic bipolar plates and lower cost manufacturing techniques. Also, it reduces thermal stress, increases durability, reduces startup time, and increases efficiency or reduces the BOP. High power densities up to 2 W/cm2 at 800C have been reported for single cells. [26, 27]. Lawrence Livermore Laboratory SOFC developers report 1.05 W/cm2 at 800 C, with a stack producing 61 watts [28]. LLNL is proposing a 20 Watts SOFC development under the Palm Power program. Argonne National Laboratory has developed a 5 kw SOFC system operating at 800 C at 56% cell efficiency. This base technology is being extended to 20 watts application. These examples indicate that LFPPR will be a good thermal match to SOFC systems.

4.1.3 FUEL SELECTION AND CHARACTERIZATION AND CARBON RESIDUE TESTS

The purpose of this subtask is to define the range of fuels that LFPPR will have to process in the field and define their carbon deposition tendencies.

It is anticipated that the LFPPR can effectively process JP8 and like fuels. A key parameter will be the relative carbon formation potential of all of the fuels of interest. As described in Section 2.1, the boiling temperature range of the fuel determines the number of carbon atoms in the fuel molecule and its carbon deposition tendency. By characterizing a range of fuels for properties and carbon formation, a limited number of fuels can then be selected to best represent a range of fuels in the laboratory tests. Also, test data obtained under this task will be useful in supporting component LFPPR design efforts.

Under this subtask, samples of JP-8 fuel from different military bases will be collected. Jet fuels are subject to MIL-T83133D and ASTM specifications. Part of this specification is shown in Table 5. As shown the boiling point range and the sulfur content are specified. Some military units deviate from these specifications. For example, the Air Force currently uses 0.2%

sulfur specification fuel. Therefore, while specifications constrain some fuel properties, there are some differences in fuel properties. Impacts of these fuel differences need to be determined at the initiation of the effort. In addition, with simple tests, the implications of handling a back up fuel in the LFPPR can be defined at the beginning of the program.

Table 5 - US Air Force JP-8 (NATAO F-34/F-35) Specification

Boiling Range, C	145-300
Sulfur, Total	0.30 % weight[3]
Density	0.755-0.840
Aromatics, % vol	25
Particulate matter mg/l	1.0

To assess the impact of fuel differences, six JP8 fuel samples, distinguished by refinery, type of crude oil and region of origin will be selected. Four diesel fuels will also be collected. Emphasis will be on selecting diesels with different boiling ranges. For example military arctic diesel has a boiling range between 100 C to 350 C, while the fuel used in warmer climates has a boiling range of 200 to 450 C. These four diesel samples will be fractionated at 300 C, the Final Boiling Point (FBP) of JP8. The purpose of this fractionation is to evaluate whether a diesel fractionated to the FBP temperature of JP-8 has a carbon deposition tendency similar to that of JP8. The six JP8 samples, four diesel samples and the four fractionated diesel samples will be sent to an outside laboratory for Micro Carbon Residue (MCR) testing. This ASTM D-4530 test defines the carbon deposition tendency of these samples.

Results will be compared to characterize the carbon deposition tendency of these samples. Of particular interest will be to compare the MCR values of the JP8 samples and the fractionated diesel. All of these samples have the same FBP and it is expected that their MCRs will be the same. If test results confirm this expectation, it will support the notion of using the LFPPR with any JP8 like fuel. More importantly, it will show the flexibility of LFPPR in being able to use any fuel, as long as the system is adjusted to fractionate the fuel to the same needed FBP prior to processing by the pre-reformer and reformer. This is an important advantage of the LFPPR. The selected fuel will also be tested at Altex to obtain fractionation versus the boiling point, similar to that shown in Figure 5. This information will be used to design the fractionator.

4.1.4 LFPPR Specs Definition

The purpose of this subtask is to refine the LFPPR specifications defined earlier in this task, and highlighted in Table 3. The fuel test results discussed above, and other information gathered will be used to further refine the LFPPR specifications. In particular, inputs will be received from the SOFC developer to update the LFPPR goals and specifications.
Also users of the Palm Power units will be contacted to receive their inputs on the conditions under which LFPPR is used and to update human factor issues that must be incorporated in the design. At the conclusion of this task, the updated specs and goals will be reviewed with DARPA, and used to update the LFPPR product design to be prepared in Task 2.

4.2. Task 2-Preliminary LFPPR/SOFC Integrated System Design

The purpose of this task is to design the integrated LFPPR and SOFC system.

At the initiation of this task, the updated LFPPR specs will be used to help define the necessary design changes. An important issue in updating the LFPPR design will be its integration the SOFC. Inputs from the FC contractor on FC specifications, will be used to define a process diagram for the integrated system. The Altex Thermo Fluid Model (ATFM), that has

[3] Recent specifications 0.2%

been used to perform preliminary LFPPR system calculations for this proposal, (see Figure 8), will be used to update process conditions. This model calculates the energy and mass balances, temperatures, flows and pressure drops. In addition to this simple global model, Altex will use the available PROF-HET [29] reactor model to calculate detailed mass and energy transport within reactor modules. This model has been used to calculate catalytic combustion of fuels in honeycomb monoliths, including gas phase chemistry, as well as surface reactions. This model is well suited to address design issues for monolith based desulfurization, pre-reformer and reformer reactors applied in the LFPPR.

As examples of the capability of the model, Figure 10 presents bulk fuel concentrations and temperature versus catalytic monolith wall conditions in the entrance region of a catalytic combustor monolith. On the plot is given the monolith circular channel diameter and void fraction, as well as other conditions. Note that this monolith is somewhat large .09 in diam with .003m channels) relative to the anticipated micro-reactor scale. However, the model is flexible enough to cover different geometries, scales and materials. As shown, the monolith wall chamber and gas conditions are initially very different, with the front of this monolith exhibiting a non-equilibrium wall state (i.e. nonzero fuel concentration and low temperature). This calculation illustrates a case where increases in reactor throughput would further lower the wall temperature at the front of the monolith and "blow out" the reaction. Therefore, catalyst kinetics at the wall are controlling the fuel conversion rate for this case and the results indicate that the flowrate is near the maximum flow rate limit of the reactor.

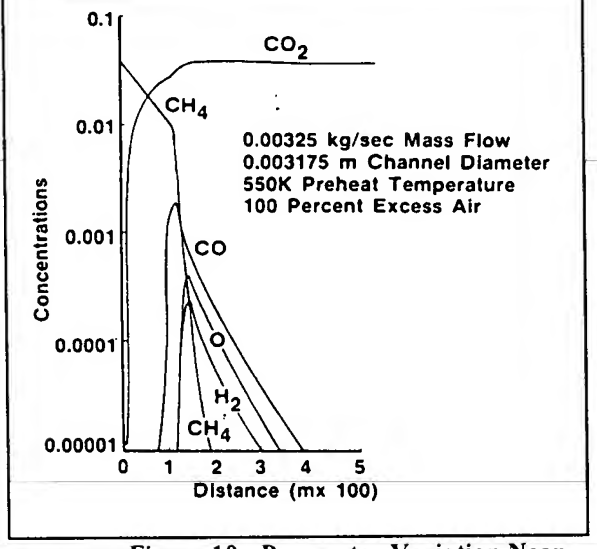


Figure 10 - Parameter Variation Near Entrance of Catalytic Combustor

In Figure 11, a PROF-HET calculation of fuel conversion in the monolith bed is given, with homogeneous gas phase reactions, as well as surface reactions active. As shown, under catalytic combustion conditions, surface reactions deplete the fuel up until approximately .014 meters. However, at this location, gas phase temperatures have risen sufficiently for homogeneous gas phase reactions, as well as surface reactions, to become active. At this point, gas phase reactions rapidly proceed, depleting the remaining fuel in a short distance, and producing CO and H_2 intermediate products prior to the final oxidation to CO_2 and H_2O. When operated as a steam reformer, rather than a combustor, results would be different. For the reformer case, available oxygen is limited and fuel reaction would be halted once H_2 and CO are produced. Therefore, H_2 and CO would exit the reactor. With the input of fuel reaction

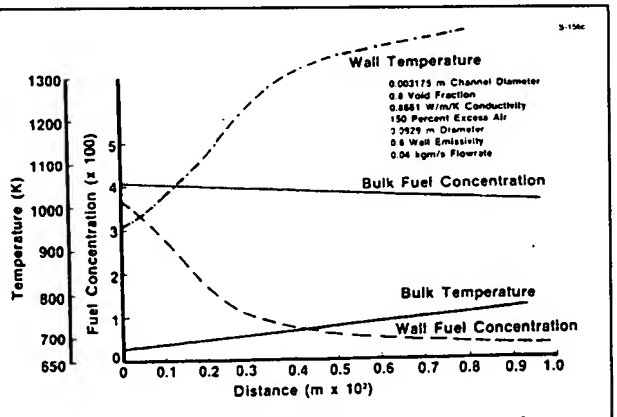


Figure 11 - Species Profiles Along Catalytic Combustor

data, the PROF-HET model could be used to help design reactor configurations. In particular, for a given flow rate and reactor volume, the model could be used to define monolith geometries and surface area-per-volume needed to achieve the needed fuel reforming. Also, once test data is obtained, it can be used in the model to update model reaction rate parameters for the more refined integrated micro-reactor design to be carried out in Task 4.

Under this task, model calculations will be performed for reformer steam to carbon ratios between 2 to 4. The higher the steam content, the higher the hydrogen content of the product gas and the less tendency to deposit carbon. The latter will be the main driver for using steam to carbon ratios greater than 2. The final steam/carbon ratio will be defined by tests. For each steam to carbon ratio, the flow rates, dimensions, pressure drops and reformer efficiency will be calculated.

In addition to system level calculations and definitions, Altex and PSU will apply models and correlations of data to design subcomponents of the LFPPR. Specific design activities for the subcomponents are highlighted below.

4.2.1 FRACTIONATOR DESIGN

The fractionator will be designed to separate fuel molecules that are characterized by C14-C17's and two-ring aromatic compounds. These are components that have a high potential for carbon formation. The boiling point associated with C14 is 253 C.

The fractionator temperature and thereby the boiling point of the separated fuel will be defined by the ATFM model. The energy balance will define the fraction of the fuel that is required to be burned in the micro-burner. As discussed in Section 2, preliminary calculations show that 30% of the fuel is required for process heat. The fuel fraction-boiling point data of Task 1 will be used to define the boiling point associated with this fraction. Based on the available JP8 data, it is estimated that this fraction is equivalent to 220 C. At this temperature, the fractionator separates out C12 to C17, which is better than the target of C14 based on carbon formation potential. This will be beneficial to reducing carbon formation potential in the pre-reformer and reformer.

4.2.2 MICRO-BURNER DESIGN

The micro-burner needs to effectively burn the heavy ends and produce heat for reforming. This burner will be based on the Altex Low Cost Pocket Stove (LCPS), developed for the U.S. Army. For the Army application, the burner output was 600W, and weighed 113 gr. Through tests and analyses on burner scales of 600W, 300W and 50W, it was found that the burner capacity is proportional to the wick length and also the screen area. Using these relationships it is estimated that the current 20W application will weigh 3 gr, and will be 1 cm long and 1 cm high. To avoid pluggage, the burner, will use the Altex Porous Surface Element (PSE) wick that pumps and vaporizes the fuel. As noted in Section 2, the PSE is designed with graded passage sizes and recessed cooler areas so that heavy ends and deposits do not plug fuel paths. The stove has been tested for extended hours under continuous and cycle operation on diesel and jet fuel. As shown in Figure 5 diesel fuel contains molecules up to C25 carbon. Therefore, the stove has already been tested over a greater range of heavy ends than are present in the jet fuel (i.e. C-14-C17). Therefore, it is anticipated that the Micro-burner will operate reliably on heavy ends.

The major difference between the LCPS and the needed micro-burner is that the latter operates with forced air flow to overcome system pressure drops. In contrast, the LCPS was designed to operate on natural draft. This made LCPS operation system dependent. The addition

of forced air should make the design approach easier, as there is independent control of the air flow. It will be designed to operate at 20-30% excess air, for optimal efficiency.

4.2.3 DESULFURIZER DESIGN

Sulfur in the fuel must be reduced to minimize catalyst poisoning in the pre-reformer and reformer. Standard approaches convert sulfur compounds to gaseous H_2S. However, for the potential man carried Palm Power application, desulfurization approaches that result in noxious H_2S, should be avoided.

The proposed desulfurizer is an Organic-Sulfur-Trap (OST) that consists of sulfur-capturing metal components, such as nickel, dispersed on an ultra-thin-wall mini-monolith. When fuel molecules flow through the OST, the sulfur will be removed quickly, but the hydrocarbon fuel molecules will pass through the device unaltered. With the OST approach, desulfurization of the JP-8 can be accomplished in a compact, and replaceable cartridge, that can also be regenerated, if necessary. For the preliminary JP8 design, Penn State will use their experience in designing an OST for gasoline, which showed that metal based adsorbent materials can make an effective OST. PSU has recently performed a detailed analysis of sulfur compounds in gasoline, JP-8 jet fuel, and a diesel fuel, sulfur analysis by GC-FPD for the three types of liquid fuels. Based on PSU's analysis, the approach of deep desulfurization by selective adsorption is a promising choice for liquid hydrocarbon fuels such as JP-8 and diesel. Certain transition metals, such as nickel, are reactive with sulfur compounds and can attach sulfur as metal sulfides. Other metals, such as zinc, can react with nickel sulfide to produce nickel metal and zinc sulfide, thereby regenerating the more reactive nickel. Computational analysis of various metal-sulfur bonding interactions will be used by PSU under the program to aid in defining the OST metals.

4.2.4 PRE-REFORMER DESIGN

As illustrated in Figure 2, the pre-reformer will consist of a honeycomb catalytic monolith reactor held in a cylindrical downflow reactor. Based on previous PSU work with JP8 fuel, the pre-reformer will be defined. Reaction calculations will be performed for the best candidates, that are envisioned to be Rh and Ru supported on ceria and zirconia. Selection of these candidates is based on the fact that Ru and Rh, when supported on zirconia, have been shown to be active at 500 °C for steam reforming of n-butane [30]. More recent study show that Rh supported on ceria can promote the cleavage of C-C bond in C2 species [31]. These are encouraging results, which also suggest that the reactor should operate at approximately 500C and atmospheric pressure.

While these materials appear promising, tests will be needed to define optimal support and catalyst materials. Prior to testing, the pre-reformer reactor will be designed using the PROF-HET model and estimates of catalyst dispersion on the substrate and assuming rapid reaction at the surface. This will then define the minimal reactor size needed. Once prototype tests are completed, reaction data can then be used to refine the reactor size.

As noted earlier, Oxygen is used in the pre-reformer to further reduce the potential of carbon formation. It is anticipated that the level of air needed is less than 10%. In the pre-reformer design, air will be added to the steam and fuel stream. Because of the small amount of air needed, consideration will be given to eductting the air into the reactor by the steam or fuel stream.

4.2.5 REFORMER DESIGN

As with the pre-reformer, the reformer consists of an ultra-thin-wall honeycomb catalytic monolith reactor held in a cylindrical downflow reactor placed below the pre-reformer, as shown in Figure 2. Based on recent PSU research on natural gas reforming, a small amount of oxygen in the flow can greatly minimize carbon formation. Therefore, this approach will be pursued in the reformer, as well as the pre-reformer. This approach is different from autothermal reforming, where substantial oxygen is used to promote heat release. In the LFPPR case, heat is provided externally by burning the heavy ends, and only a small amount of oxygen is used internally to address carbon formation and deposition. With this approach, efficiency of conversion is higher than with autothermal reforming as noted in Section 2.2.

As with the pre-reformer, ceria or zirconia based ultra-thin-wall monoliths will be evaluated for use with a wash coat impregnated with a noble metal catalyst, such as platinum. The reactor will be designed to operate at approximately 850C at nearly atmospheric pressure. This condition will favorably overlap with the operating temperature of the SOFC.

Based on PSU experience and assessments of the literature, the reformer design should be able to meet component goals. However, tests are needed to define optimal materials and configurations. Prior to these planned tests, the reformer reactor will be designed using the PROF-HET model using estimates of catalyst dispersion and assuming a level of rapid reaction at the surface. As with the pre-reformer, these calculations will define the minimal reactor size needed. Once tests are completed, reaction data can then be used to refine the reactor size.

4.2.6 SYSTEM DESIGN

Under this subtask, component designs will be integrated together to create the system design. Also, fuel and water pumps, air fan and controls will be defined for the system. Heat transfer calculations will be used to define the gas velocity and the surface area, including fins, needed to transfer heat from the micro burner exhaust to the reformer, pre-reformer, OST and fractionator. Calculations will also define the pressure drop and the air fan needs. Under this subtask, the system insulation needs will also be defined. Given the high surface area per volume of the LFPPR system, highly effective insulation is needed, particularly for high temperature sections. Advanced Modular Power Systems (AMPS) MLI metal foil/ceramic beads insulation has both excellent conductivity and weight characteristics. The adaption of this material to the LFPPR will be explored under this task.

System controls will also be defined in this task. In the preliminary design of Figure 2, a valve is incorporated that controls the flow of the hot gas around the fractionator. Valves exist or can easily be developed that open and close at a preset temperature. These valves function either based on bi-metallic strips, or evaporation of a liquid at the control temperature. These are low weight valves that do not require an elaborate control system. It is envisioned that these types of valves can be used in the system. In addition to valves, small pumps and controls for fans and pumps will be incorporated in the design.

The issues with system startup will also be defined under this subtask. Starting the external burner will make it easy to heat up the system. Since the micro-burner is flexible, it can be started on JP8. This will heat up the reactor beds. Due to the low thermal mass of the system, heat up should be quick. Calculations will be made to define the start-up period. If required, a larger micro-burner with a wider turn down will be incorporated, for a more rapid startup. Another approach would be to introduce more air into the reactor at startup to promote more heat release and faster heatup. Implications on system operation will be assessed under this task.

After the LFPPR design process is completed, a fault-tree failure mode analysis will be performed by Altex, PSU and the SOFC contractor. This will be used to assess the potential failure modes of the system and the degree of severity and probability of occurrence for each component. Results will be useful for providing a systematic basis for evaluating safety issues early enough in the design process to allow modifications to minimize risk.

At the completion of the design effort, it will become clear what design data gaps exist and need to be filled by tests in Task 3. Some obvious areas include the specification of optimal monolith and catalyst characteristics for the pre-reformer and reformer as well as overall reactor length. Many other areas will require testing prior to finalizing the design. These tests will cover fractionator, micro-burner, desulfurizer, pre-reformer and reformer components. An important issue related to component testing will be the scale of the prototype tests.

Prototype component tests must provide good instrumentation access to fully characterize performance. Therefore, component sizes might have to be larger then those ultimately integrated together to create the Micro Reactor. Fortunately, the OST, pre-reformer, and reformer use ultra-thin wall monoliths that can be easily scaled, based on cross sectional area. Therefore, prototype tests of these components can be done at increased scale, with test results directly relevant to the Micro Reactor system. Also, based on Altex experience, the Micro-burner can be easily scaled. Scaling issues of all components will be reviewed under this task and prototype scales defined for tests to be conducted in Task 3.

As noted in the above discussion, there are several challenges with JP8 fuel processing that carry risk. The LFPPR, by employing several JP8 processing steps helps balance the risk, particularly for carbon disposition. Some of the risks and strategies to reduce risks are highlighted in the table below. During the proposed effort, other risks will be uncovered and Altex and PSU experience will be used to define strategies to control these risks.

Carbon deposition	Decrease fractionator temperature Increase oxygen assist Increase steam to carbon ratio Incorporate more pre-reforming Redefine catalysts
Liquid fuel carryover into reactors	Incorporate baffle separator or coarse filter
Micro burner wick pluggage	Modify PSE design
Sulfur breakthrough	Over design OST Monitor sulfur Increase cartridge replacement frequency
Use of wrong fuel	Design a reservoir for excess heavy ends

At the completion of this task, both component and integrated system designs will be available for review by project participants and DARPA. Following review by participants and DARPA, final design updates will be prepared, prior to proceeding to the prototype reactor tests.

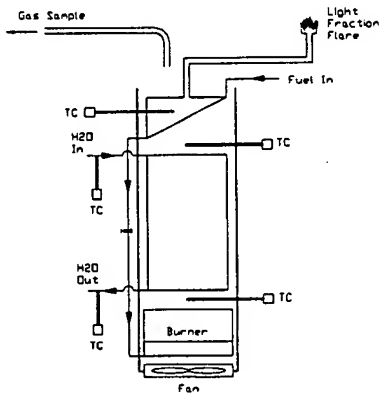


Figure 12- Fractionator/Micro-Burner Integrated Test System

4.3. TASK 3-PROTOTYPE REACTOR DESIGN, FABRICATION AND TEST

The purpose of this task is to fabricate a prototype LFPPR for laboratory testing and evaluation. Initially, a prototype of each component will be designed, fabricated extensively instrument and

tested, to resolve performance issues concerning each element. Then all the elements will be integrated together to test the complete prototype system. To help optimize performance, some flexibility will be built into prototype test articles. To help design LFPPR elements, the same models used to design the system will be employed, including the ATFM and PROF-HET models. In addition, prior Altex and PSU test and analyses results will be used to support test system design.

4.3.1 FRACTIONATOR AND MICRO-BURNER DESIGN, FABRICATION AND TEST

The fractionator and micro-burner test articles will be developed together. This will ensure that questions related to their integration are addressed early on in the program. Figure 12 shows the test setup. This system will be designed to simulate the integrated system flows, heat loads and temperature profiles. As shown, similar to the integrated system illustrated in Figure 2, the micro-burner is located at the bottom of a tube, with the fractionator located at the top. The fractionator is simply a cylindrical container with a sloped surface to allow the fuel to flow down, as the light fractions are evaporating. To simulate the pre-reformer and reformer heat load for the integrated system, an air cooled element will be placed between the micro burner and the fractionator. By controlling the amount of air flowing through this unit, different heat loads can be simulated. The sizes of passages will be selected to have the same pressure drop as in the 20 watts integrated system. The unit will be instrumented with thermocouples, to measure the fractionator, and gas temperatures. A gas sampling probe, shown in Figure 12, will be used to measure O_2, CO, unburned hydrocarbons, CO_2, and NOx. The needed continuous emissions monitoring equipment is available at Altex. The data collection is computer controlled for a rapid testing cycle and post test evaluation and analysis.

The micro-burner design and development will make full use of the Altex LCPS development experience obtained under the Army project. The Micro-burner will consist of a stamped thin metal reservoir that holds the PSE wick. Vaporized fuel is then mixed with the air that is entrained through the perforated screens. The PSE AMETEK ceramic woven fiber wick is designed to draw the fuel from the reservoir and evaporate the fuel without plugging the wick. Using the available heat output versus wick length and heat output versus screen area correlations, the micro-burner wick length and screen area can be determined. Stainless steel or superalloy perforated screens will be specified. Screen thickness, hole size and hole pattern will be based on experience obtained under prior Army developments.

To start up the burner, a small electric wire resistance heater will be embedded into a short section of the center edge of the wick. During startup, battery power will be used to vaporize a small quantity of fuel from the wick. A standard piezoelectric spark type igniter will be placed in close proximity to a portion of the heated wick to ignite the vapor. Once a flame is initiated, it will heat the wick and promote ignition of the entire wick. As noted earlier, this ignition approach has been demonstrated in Altex LCPS tests on diesel fuel. Given the success with diesel fuel, it should be even easier to ignite JP8.

Tests will be planned to demonstrate how the fractionator and micro-burner operate together. Anticipated tests, to be included in a test plan, are listed in Table 6.

Table 6 - Fractionator and Micro Burner Element and Integrated System Tests

Fractionator Temperature Ranges The fractionator temperature range will be varied to define its effectiveness in fractionating the fuel.
Heat Output and Heat Transfer The fuel flow rate will be measured and compared to the measured heat generation rate, calculated from the load and the exhaust conditions.
Burner Orientation Burner operation in various orientations will be tested
Emissions Emissions and O_2 will be measured to define flame quality. Emissions will be compared to the goals.
Cold and Hot Temperature Operation The burner will be subjected to temperatures down to –18C (0F) in a cold chamber and up to 52C (125F) in a hot chamber and then tested.
Fuel Flexibility Burner performance will be evaluated on JP-8, and back up fuels defined in Task 1.
Consistency of Heat Output Over Time The burner will be cycled on and off for over 1000 cycles

Initial tests will focus on proper operation of the micro-burner. For the specified heat load, the burner will be brought to steady operation and measurements of emissions, temperatures and flow rates recorded.

A key parameter to check early on is the excess oxygen level in the exhaust, as well as CO and unburned hydrocarbons. An exhaust oxygen level of 3% is planned. If the oxygen level is significantly above or below this level, the air flow will be adjusted. At the needed 3% oxygen level, CO and unburned hydrocarbon emissions should be reasonable. For CO, the Canadian Gas Association (CSA) standard procedure B 14092-1975 will be applied. Besides checking emissions, exhaust visibility will also be monitored, using standard Ringleman plume opacity assessments. Heat output and heat transfer tests will determine delivered energy. Also, load temperature as well as heat transfer to the load will be monitored by thermocouples. Temperatures of the fuel reservoirs, wick, screens and fractionator will be monitored and reviewed to ensure all temperatures are within the design range for good durability over long term operation

During operation, samples of the fractionated fuel will be collected as a function of fractionator temperature. The boiling point fractions of the fuel will be determined and compared with equilibrium based theoretical boiling point levels, based on measured temperatures. Also, periodically the fractionator chamber and micro-burner supply line will be inspected for any residue buildup.

Once steady and acceptable operation is achieved at base load, the air flow and fuel flow will be modulated to reduce load, as per the specs. As in the baseline test, emissions and temperature will be carefully monitored during load variations and at startup and shutdown, and any deviation from the acceptable range will require design modifications. The performance of the fractionator and any change in residue as fuel flow is reduced will be monitored.

As listed in Table 6, once burner/fractionator operation has been found acceptable under standard conditions, several tests will be performed to assess operation under different environments. An available cold chamber will be used to test the burner down to -18C and up to 52C. Also, as part of these environmental tests, the burner fractionator will be operated on backup fuels.

After the basic performance tests are completed, the burner/fractionator will be operated for 1000 cycles over 200 hours of cycled use and inspected on a periodic basis to note degradation or clogging, and any other component degradation. Output capacity drop off with time and emissions or temperature excursions will be used as a measure of degradation. Also, the system will be disassembled and visually inspected to note any degradation. The Altex Burner Cycle Test Facility, will be utilized for cycle testing. This facility has computer actuated solenoids that can be used to cycle the micro-burner/fractuator system on and off over many cycles. The facility has built in safety features to ensure safe operation without constant personnel oversight.

At the completion of micro-burner/fractionator tests, Altex will review the results with PSU and DARPA and conclude on the viability of the micro-burner/fractionator design. If the design looks favorable, it will be carried over to the integrated prototype system tests. It should be noted that the prototype Micro burner/fractionator unit will be used as a base for integrated components tests. This will be accomplished by replacing the OST, pre-reformer and reformer simulation elements by actual honeycomb monolith reactor elements developed in PSU tests. Given that honeycomb monoliths can be easily scaled, based on frontal area, prototype tests of OST, pre-reformer and reformer elements can take place in laboratory scale reactors at PSU.

4.3.2 DESULFURIZER DESIGN, FABRICATION AND TESTS

A flow chart of existing desulfurization unit is shown in Figure 13. For the proposed project, an ultra-thin-wall monolith core will be used to screen candidate sulfur adsorbents for desulfurization. In the reactor, a stainless steel tube of 1 cm in diameter, which contains the adsorbent, is heated by an electric furnace. The PSDTS is designed to operate between 30°C and 450°C temperature.

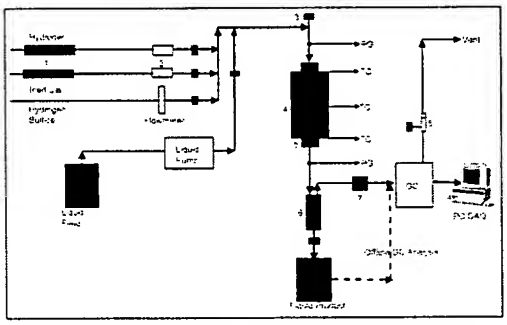


Figure 13- Penn State Reforming Test Unit Diagram

By varying the temperature, the optimal temperature for best sulfur removal efficiency will be defined. JP8 is pumped into the vaporizing unit, and fed into this desulfurization reactor in the temperature range of 250-400°C. The monolith tube in the OST will be designed to handle 0.064 cc to 0.128 cc (JP8 liquid)/min. The liquid flow rate of 0.128 cc/min is equivalent to 80 watts in terms of calorific value of JP8. This is approximately 4 times the expected flow in the Palm Power system. However, the monolith projected for use has a simple scaling relationship and data form the prototype can be directly extrapolated to the Micro reactor system.

During tests, the flow, temperature, pressure and the sulfur concentrations will be measured continuously, and data will be collected for later analysis. Initial screening tests will be run for 6 hours. Based on PSU experience, this period is sufficient to identify promising materials and to define the effectiveness of the adsorbents.

For each test, the OST will be prepared by loading potential candidate desulfurization metal species on an ultra-thin-wall monolith. The candidate metal components include a binary system consisting of two metal species such as nickel and zinc, and monometallic adsorbent based on palladium compounds. Computational analysis of various metal-sulfur bonding interactions will be conducted by PSU to aid in screening metal components for use as

adsorbents. As shown in Figure 7, the proposed approach has been established in our recent work for gasoline and we will develop materials that are suitable for use with logistic JP8 fuel.

After the initial screening, the promising OST candidates will be tested for up to 72 hours to define OST efficiency over time. Based on these tests and calculations, the replacement frequency of the OST cartridge will be defined. The OST will be made into a replaceable cartridge, so that a new OST can be inserted into the micro fuel processor system as a cartridge.

4.3.3 Pre-Reformer Design, Fabrication and Tests

Materials for the oxygen assisted pre-reformer will be developed by screening potential catalysts at low-temperature in the Penn State Reforming Test Unit (PSRTU). The existing natural gas-based PSRTU can be modified so that liquid fuel can be fed by an accurate liquid-feed pump and then vaporized inside the reactor. A diagram of the reactor in the existing PSRTU is shown in Figure 14. The reactor dimensions are 0.8 cm in diameter and 43 cm in length. Only about 1 cm of the tube is for catalyst loading. Other system components will be the same as those for the reformer described below.

The candidate catalysts to be studied for pre-reforming will be those consisting of Rh or Ru dispersed on CeO_2 or ZrO_2. Such catalysts will be loaded by wash-coating impregnation techniques onto ultra-thin-wall monoliths to form the micro-chemical reactor for pre-reforming. Catalyst screening will be performed at atmospheric pressure in the temperature range of 450-550°C. The products will be identified by GC and GC-MS and quantified by GC. For comparison, commercially available formulations with nickel metal and alumina support will be tested as a reference case. However, such commercial catalyst is expected to encounter quick deactivation, due to rapid carbon formation. The activity and selectivity of all the catalysts will be assessed based on the liquid conversion and products distribution.

The initial screening experiments will be conducted for 6 hours. Promising catalysts will then be tested for 72 hours, to define the effectiveness of the catalyst and optimal process conditions. The promising pre-reforming catalysts will also be evaluated for their resistance to carbon formation, as described below, which is an important part of the micro-fuel processor development effort.

4.3.4 Reformer Design, Fabrication and Tests

Under this task, candidate reformer catalysts will be selected and prepared and then tested in the PSRTU. PSU will screen potential catalytic materials that have transition metal (Ru, Rh, Pt, Ni, Ni-Mo, Ni-w) dispersed on supports that have oxygen-spill-over capability, such as ceria (CeO_2), zirconia (ZrO_2) and titania (TiO_2). Both precious metals (1 wt% based on support) and non-precious metals (10 wt% based on support) will be tested in the initial work. The industrial steam-reforming catalysts, in which nickel is supported on magnesia (MgO) and alumina (Al_2O_3) substrates, will be used as reference for comparison. The resistance to coking and activity level and stability for oxygen-assisted steam reforming will be the criteria for selecting catalytic metal and support materials for screening.

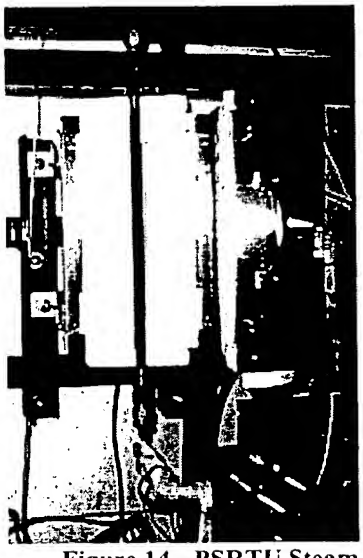


Figure 14 - PSRTU Steam Reformer

The candidate catalysts will be loaded by wash-coating impregnation techniques onto ultra-thin-wall monoliths. Catalyst screening will be performed in the PSRTU continuous-down-flow tubular reactor at atmospheric pressure in the

temperature range of 650-900°C. These screening conditions also incorporate a temperature window that overlaps with an optimum range of operating temperatures for solid-oxide fuel cells. This should allow easier integration of the proposed micro-fuel processor into the SOFC system.

A key aspect of the LFPPR, and pre-reformer and reformer in particular, is carbon formation in the system. Therefore, carbon formation aspects will have to be carefully quantified. Pre-reforming and reforming catalysts will be evaluated for their resistance to carbon formation, using a tapered element oscillating microscope (TEOM) apparatus. A tapered element oscillating microscope (TEOM) apparatus has been purchased and coupled with the steam reforming reactor in the PSU laboratory, which allows the dynamic characterization of carbon formation under real feed flow conditions during steam reforming at elevated temperatures under either atmospheric-pressure or elevated pressure, as described in a recent PSU paper [32, 33]. The TEOM has a 0.25 cc catalyst cell, through which all the feed gas/vapor will flow through (without an bypass in the cell), thus functioning like a reactor while allowing carbon formation to be monitored simultaneously in the order of micro seconds.

PSU will conduct both an experimental study and a computational thermodynamic analysis on carbon formation for reforming of hydrocarbons in JP8. Our computational thermodynamic analysis will serve to identify and predict regions and conditions for carbon formation from higher hydrocarbons, according to the methodology PSU used for reforming natural gas [34]. A complex system is involved in such computational analysis, because PSU needs to consider the numerous components present in the higher hydrocarbon reforming system and thus the calculation is much more complicated compared to the case of natural gas. The calculation result would depend on what components are present under the equilibrium state. PSU will obtain some qualitative information on how many compounds are present in the products from GC analysis of real reaction products, and feed back such information to the computational analysis.

For both pre-reforming and reforming catalysts, PSU will use the TEOM apparatus and a temperature-programmed bulk carbon analyzer coupled with spectroscopic techniques to characterize the carbon formation of pre-reforming and reforming catalysts proposed in this work. A Leco Carbon Analyzer allows the quantitative analysis of carbon on the shaped/formed catalysts such as monoliths. The carbon formed on the catalyst surface will then be characterized by scanning electron microscope (SEM) and transmission electron microscope (TEM).

The information from this task will be carefully analyzed and then fed back to the sub-tasks on pre-reforming and reforming, for developing catalysts that are more resistant to carbon deposition.

4.3.5 Design Test and Evaluate Prototype System - Altex

The purpose of this subtask is to design and fabricate a LFPPR prototype test system and to use it to test and evaluate integrated system performance, reliability, and long term and transient operation.

Prior to designing the integrated LFPPR Microreactor for integration with a SOFC, the tested prototype elements need to be integrated together and tested as a complete system. This will identify problems and performance levels for the overall system. In addition, by integrating the elements together, long term operability can be evaluated. This information will be useful in preparing the design for the fully integrated Microreactor that will be tested in Task 4.

As noted in Figure 12, the micro-burner and fractionator prototype test system has OST, pre-reformer and reformer heat load simulators incorporated into the design. For the prototype integrated system tests, the heat load simulator will be replaced by a module that contains the

OST, pre-reformer and reformer monolith beds developed and tested at PSU. These beds will be loaded into a metal heat transfer shroud and steam and air access lines and injectors attached to duplicate operation as set up at the PSU laboratory. The shroud will be designed with needed insulation and fins, where needed, to ensure that the individual optimal monolith operating temperatures are achieved for the three beds. By utilizing the existing micro-fractionator test setup at Altex, the integrated system can be quickly commissioned. In addition, by utilizing proven fractionator and burner components, technical risk will be reduced.

Integrated prototype system tests will cover the sequence listed in Table 8. For the baseline tests, the performance under baseline flow rate conditions will be determined. During testing, the output of the system, including emissions, will be monitored as well as critical temperatures and pressures at the fixed fuel flowrate. If pressures, temperatures, emissions or the product gas are not within the specified range, system adjustments will be made. For example, the air versus fuel flow can be adjusted to change gas temperatures as well as impact emissions. This control could be implemented to adjust reactor temperatures to the needed range. In addition to monitoring instruments to assess performance, the unit will be disassembled after testing to check for carbon deposit or residue buildup.

Once baseline tests results are acceptable, tests where load is varied will be carried out. In this case, fuel and air flow to the Micro-burner will be adjusted, as well as steam and air flow to the reactors. Again, flows, temperatures, emissions and product gas composition will be monitored and deviations from accepted ranges will be noted. If needed, the system design will be updated, and the system retested, to ensure it remains within accepted ranges.

Once load variation tests are successful, startup/shutdown transient performance tests will be run. Parameter excursions outside accepted ranges will be noted, and the system updated, as needed, to address any problems. An important test will be the longevity tests. For this test, the LFPPR system will be installed in the Altex Burner Cycle Test Facility and system on-steady-off operation tests run for 240 hours. These tests will be similar to those run under the Micro-burner/fractionator prototype component test task. To evaluate performance changes over time, product and emissions characteristics will be monitored, as well as temperature measurements. At the completion of this test, the system will be disassembled and inspected for carbon residue deposition. Environmental tests will be run in the cold chamber, down to -18C and in the hot chamber up to 52C. This will identify any problem when operating either under cold or hot environments. Lastly, fuel flexibility tests will be run to determine the range of fuels that the LFPPR is capable of processing. It is anticipated that diesel to kerosene fuels will be tested. The specific fuels selected for testing will be based on assessments carried out under Task 1. These fuels will be approved for testing by DARPA.

Table 8 LFPPR Integrated Prototype System Tests

Test	Purpose
Baseline Operation	Prove viable operation at standard conditions
Load Variation	Establish performance as load is varied
Startup/Shutdown	Characterize transients and problem characteristics
Longevity Tests	Determine durability and performance over longer term operation
Environmental Tests	Check operation under cold and hot conditions
Fuel Flexibility	Determine impacts of fuel variations

At the conclusion of this task, a summary of performance results, covering fractionator/micro-burner, OST desulfurizer, pre-reformer and reformer test results will be prepared for review. These results will include information on output, load following, thermal and visual and acoustic signature, reliability, safety, and ease of operation. The results will then be compared with the

LFPPR goals and specifications. Altex, Penn State, SOFC developer and DARPA personnel will meet to review results. Based on the review, the team will conclude on the viability of the LFPPR, when integrated with a SOFC, to meet the needs of the Palm Power program. If the LFPPR has the needed potential, work will be initiated on LFPPR Microreactor design.

4.4. TASK4-DESIGN, FABRICATE AND TEST MICROREACTOR

The purpose of this task is to design, fabricate and test the LFPPR micro-reactor integrated with a 20 watts SOFC.

Under this task, the LFPPR system design prepared in Task 2 will be refined. Design procedures utilized under Task 2 will also be followed in this task. Given the substantial data base derived from Task 3, the final design refinements will be firmly supported. Furthermore, refined system design and test data will be available from the SOFC contractor. Based on inputs from previous tasks, the process diagram will be updated. At this point, SOFC process data will be included in the overall design. Final design changes at this stage are expected to focus on issues associated with minimizing weight and size, tightly integrating components, enhancing reliability, and improving ultimate manufacturability. Also some of the flexible features built into the prototype system will be eliminated at this stage, to simplify the design and reduce weight. During the design process, the fabricator, Compatible Manufacturing will be consulted to enhance the manufacturability of the final FPRR design. Once the LFPPR design is completed, a Fault Tree/Failure Mode Analysis of the integrated system will be generated to evaluate product safety considerations prior to fabricating the system. In the analysis, potential failure modes will be identified, and the degree of severity and probability of occurrence will be estimated. Results will be reviewed and prioritized, and the design updated to minimize risk. Recommended design refinements will then be reviewed by the SOFC developer and DARPA. Inputs from the SOFC will then be incorporated into the design and reviewed with DARPA. Upon design approval by the SOFC contractor and DARPA, the refinements will be implemented and fabrication will be initiated.

Compatible Manufacturing Incorporated will fabricate metal parts. The substrates and catalysts will be fabricated by PSU. Altex will fabricate ceramic wick and screen components. Upon receipt of fabricated components, Altex will inspect part quality and request rework of parts, as needed. Altex will then assemble all components, including the SOFC, in preparation for needed testing. The completed LFPPR/SOFC system will then be installed in the Altex SCET and instrumented. The instrumentation will follow that used in the prototype tests. Flow, temperature, and emissions equipment, as employed in prototype tests, will be utilized. In addition, electric power characterization instrumentation will be included to evaluate SOFC performance.

Microreactor tests to will follow those carried out in prototype testing and listed in Table 8. However, the Microreactor will have less flexibility then the prototype system. Therefore, test sequences will be shorter, with only limited adjustments. In addition, the SOFC will be integrated into the system, and electric power performance measurements will be made as well as LFPPR performance parameter measurements.

Baseline tests will cover simple operation at standard conditions, with measurements of temperatures, emissions and electrical parameters showing any deviation from accepted levels. Similar measurements and assessments will be made under load variations and transient startup and shutdown. Given the advanced state of development and success of prototype tests, it is anticipated that Microreactor performance will be within the expected range.

Given successful short-term performance tests, a 240 hour on-steady-off test will be run in the Altex Burner Cycle Test Facility. After the successful conclusion of this test, the system will be disassembled and inspected for carbon and residue formation and degradation of components.

Once the longevity test is completed, the unit will be tested in the cold chamber down to -18C and in the hot chamber up to 52C. Following successful environmental tests, the unit will be tested on a range of fuels. These fuels will be selected with the input of the SOFC contractor and DARPA. It is anticipated that a heavy fuel, such as diesel, as well as lighter fuel, such as kerosene, will be run to determine the fuel flexibility of the unit. Once each of these tests are completed, the unit will be disassembled and inspected to determine carbon and residue deposition, as well as component degradation.

Once the Altex tests are concluded, the unit will be shipped to the SOFC contractor for further testing that will focus on the SOFC. Also, following SOFC contractor testing it is anticipated that DARPA will identify a military service group that will carry out brief field testing of the unit as a simple battery charger. These tests will be valuable to get a first assessment of ease of use in the field and any operator related problems.

4.5. TASK5-EVALUATE SYSTEM

The purpose of this task is to perform a thorough and final evaluation of the LFPRR and produce needed project reports.

Based on the Microreactor test results, as well as prior prototype test results and analyses, Altex, PSU and the SOFC contractor will determine how well the LFPPR has met Palm Power goals, as integrated with a SOFC. Besides evaluating performance, the, durability and safety, maintenance will also be evaluated. A conclusion will then be reached on the viability of the LFPPR for Palm Power applications when integrated with a SOFC. In addition, Altex will obtain other FC technologies from DARPA, and a brief assessment of how the LFPPR could support these technologies will be prepared. The actual LFPPR/SOFC performance, and expected alternative LFPPR/FC performance, will then be compared to the performance of other power systems, and the advantages of the LFPPR approach identified. These evaluations and results will then be reviewed with DARPA to assess the viability of the LFPPR with selected FC systems. DARPA will then reach a conclusion on the viability of the LFPPR for Palm Power applications.

In addition to final evaluation, all reporting requirements will be executed under this task. Progress reports will cover project status and plans, and highlight any problems and correction strategies. Also, a final report, documenting the complete results of the effort will be prepared under this task. At the end of this task, a brief systems development and test plan will be prepared. This plan will determine which military systems would be high potential candidates for the LFPPR based power system, and what performance benefits would be expected by adapting the LFPPR to this military system. Also, the plan would highlight the materials, manufacturing process, and production equipment to be utilized to produce the power system. This plan will be useful in assessing the benefits of applying the integrated power system to an important military application.

5.0 STATEMENT OF WORK, SCHEDULE AND MILESTONES

5.1. TASK 1 - APPLICATION DEFINITION, FUELS ASSESSMENT AND SELECTION AND PLAN PREPARATION

At the beginning of this effort, team members, including Altex and Penn State will meet with DARPA to discuss and update project goals, technical approach, tasks and schedules. During the meeting, goals will be reviewed and updated, as required, with the concurrence of DARPA. FC technologies and contractors selected by DARPA will be reviewed and, with the help of DARPA, a FC contractor will be selected for integration with the LFPPR project. Once the FC contractor has been selected, Altex will contact and meet with the contractor to plan cooperative activities throughout the length of the project. Also, the FC contractor will provide inputs that will be used to further refine the LFPPR specifications. Ideal input conditions for the FC will be defined in consultation with the FC contractor. The first target application of the LFPPR will be a 20w SOFC.

Based on updated goals and updated approaches, Altex and PSU will then prepare a project plan, covering tasks, schedules, important milestones, deliverables and detailed budgets for the complete effort. The plan will then be transmitted to DARPA for review and approval. Once approved, the plan will be used to guide the effort.

Samples of JP-8 fuel from different military bases will be collected. To assess the impact of fuel differences, six JP8 fuel samples, distinguished by refinery, type of crude oil and region of origin will be selected. Four diesel fuels will also be collected. The six JP8 samples, four diesel samples and the four Altex fractionated diesel samples will be sent to an outside laboratory for Micro Carbon Residue (MCR) testing. MCR results will be compared to characterize the carbon deposition tendency of these samples. Of particular interest will be to compare the MCR values of the JP8 samples and the fractionated diesel. The selected fuels will also be tested at Altex to obtain fractionation versus boiling point data. This information will be used to design the fractionator.

Fuel test results, and other information gathered will be used to further refine the LFPPR specifications. Inputs will be received from the SOFC developer to update the LFPPR goals and specifications. Also users of the Palm Power units will be contacted to receive their inputs on the conditions under which LFPPR is used, and to update human factor issues that must be incorporated in the design. At the conclusion of this task, the updated specifications and goals will be reviewed with DARPA, and used to update the LFPPR product design to be prepared in Task 2.

5.2. TASK 2-PRELIMINARY LFPPR/SOFC INTEGRATED SYSTEM DESIGN

The updated LFPPR specs will be used to help define design changes. The Altex Thermo Fluid Model (ATFM) will be used to update process conditions. In addition, Altex will use the PROF-HET reactor model to calculate mass and energy transport, and chemical reaction within reactor modules. Model calculations will be performed for reformer steam to carbon ratios between 2 to 4. For each steam to carbon ratio the flow rates, dimensions, pressure drops and reformer efficiency will be calculated.

The fractionator will be designed to separate out fuel molecules that are characterized by C14-C17's, and two-ring aromatic compounds. The fractionator temperature and thereby the boiling point of the separated fuel will be defined by the ATFM model. The energy balance will define the fraction of the fuel that is burned in the micro-burner.

The Micro burner design will be based the Altex Low Cost Pocket Stove (LCPS). It will be designed to operate at 20-30% excess air, for optimal efficiency.

PSU will use their gasoline fuel experience in designing the OST for JP8. Computational analysis of various metal-sulfur bonding interactions will be used by PSU to aid in defining metal adsorbents for the OST. Nickel dispersed on an ultra-thin-wall monolith will be considered for the design.

The pre-reformer reactor will be designed to operate at 500C and one atmosphere using the PROF-HET model. In the PSU pre-reformer design, air will be added to the steam and fuel stream, and zirconia based ultra-thin-wall monoliths will be evaluated by PSU for use with a wash coat impregnated with Ru or Rh.

The reformer reactor will be designed to operate at 850C and one atmosphere using the PROF-HET model. Ceria or zirconia based ultra-thin-wall monoliths will be evaluated by PSU for use with a wash coat impregnated with a noble metal catalyst, such as platinum.

Component designs will be integrated together to create the system design. Fuel and water pumps, air fan and controls will be defined for the system. Heat transfer flow and reaction calculations will be used to help integrate all components.

After the LFPPR design process is completed, a fault-tree failure mode analysis will be performed by Altex, PSU and the SOFC contractor. This will be used to assess the potential failure modes of the system, and the degree of severity and probability of occurrence for each component.

At the completion of this task, both component and integrated system designs will be available for review by project participants and DARPA. Following review by participants and DARPA, final design updates will be prepared, prior to proceeding to the prototype reactor tests.

5.3. TASK 3-PROTOTYPE REACTOR DESIGN, FABRICATION AND TEST

A prototype of each component will be designed, fabricated, extensively instrumented, and tested to resolve performance issues concerning each element. All elements will then be integrated together to test the complete prototype system. To help design LFPPR test elements, the same models used to design the system will be employed, including the ATFM and PROF-HET models. In addition, prior Altex and PSU test and analyses results will be used to support test system design.

The fractionator and micro-burner test articles will be developed and tested together. This system will be designed to simulate the integrated system flows, heat loads, and temperature profiles. The unit will be instrumented with thermocouples, to measure the fractionator, burner and gas temperatures. A gas sampling probe, will be used to measure O_2, CO, unburned hydrocarbons, CO_2, and NOx. To assess carbon deposition impacts, the unit will be disassembled and inspected after testing.

Tests will be planned to demonstrate how the fractionator and micro-burner operate together. Anticipated tests, to be included in a test plan, are listed in the below table.

At the completion of micro-burner/fractionator tests, Altex will review the results with PSU and DARPA and conclude on the viability of the micro-burner/fractionator design. If the design looks favorable, it will be carried over to the integrated prototype system tests.

To characterize the OST process, an ultra-thin-wall monolith core will be used to screen candidate sulfur adsorbents for desulfurization. The candidate metal components include a binary system consisting of two metal species such as nickel and zinc, and monometallic adsorbent based on palladium compounds. Computational analysis of various metal-sulfur bonding interactions will be conducted by PSU to aid in screening metal components for use as

adsorbents. During tests, the flow, temperature, pressure and the sulfur concentrations will be measured continuously, and data will be collected for later analysis. Initial screening tests will be run for 6 hours. After the initial screening, the promising OST candidates will be tested for up to 72 hours to define OST efficiency over time. Based on these tests and calculations, the replacement frequency of the OST cartridge will be defined.

Fractionator and Micro Burner Element and Integrated System Tests

Fractionator Temperature Ranges The fractionator temperature range will be varied to define its effectiveness in fractionating the fuel.
Heat Output and Heat Transfer The fuel flow rate will be measured and compared to the measured heat generation rate, calculated from the load and the exhaust conditions.
Burner Orientation Burner operation in various orientations will be tested
Emissions Emissions and O_2 will be measured to define flame quality. Emissions will be compared to the goals.
Cold and Hot Temperature Operation The burner will be subjected to temperatures down to –18C (0F) in a cold chamber and up to 52C (125F) in a hot chamber and then tested.
Fuel Flexibility Burner performance will be evaluated on JP-8, and back up fuels defined in Task 1.
Consistency of Heat Output Over Time The burner will be cycled on and off for over 1000 cycles

Materials for the oxygen assisted pre-reformer will be developed by screening potential catalysts at low-temperature in the Penn State Reforming Test Unit (PSRTU). The candidate catalysts to be studied for pre-reforming will be those consisting of Rh or Ru dispersed on CeO_2 or ZrO_2. Catalyst screening will be performed at atmospheric pressure in the temperature range of 450-550°C. The products will be identified by GC and GC-MS and quantified by GC. For comparison, commercially available formulations with nickel metal and alumina support will be tested as a reference case. The initial screening experiments will be conducted for 6 hours. Promising catalysts will then be tested for 72 hours to define the effectiveness of the catalyst and optimal process conditions. The promising pre-reforming catalysts will also be evaluated for their resistance to carbon formation, as described below.

Candidate reformer catalysts will be selected and prepared and then tested in the PSRTU. PSU will screen potential catalytic materials that have transition metal (Ru, Rh, Pt, Ni, Ni-Mo, Ni-w) dispersed on supports such as ceria (CeO_2), zirconia (ZrO_2) and titania (TiO_2). Both precious metals (1 wt% based on support) and non-precious metals (10 wt% based on support) will be tested in the initial work. The industrial steam-reforming catalysts, will be used as a reference for comparison. Catalyst screening will be performed at atmospheric pressure in the temperature range of 650-900°C.

Carbon formation aspects will be carefully quantified. Pre-reforming and reforming catalysts will be evaluated for their resistance to carbon formation, using a Tapered Element Oscillating Microscope (TEOM) apparatus. PSU will conduct both an experimental study and a computational thermodynamic analysis on carbon formation for reforming of hydrocarbons in JP8. The computational thermodynamic analysis will serve to identify and predict regions and conditions for carbon formation from higher hydrocarbons. For both pre-reforming and reforming catalysts, PSU will use the TEOM apparatus and a temperature-programmed bulk carbon analyzer coupled with spectroscopic techniques to characterize the carbon formation of

pre-reforming and reforming. The carbon formed on the catalyst surface will then be characterized by scanning electron microscope (SEM) and transmission electron microscope (TEM).

For the prototype integrated system tests, the heat load simulator will be replaced by a module that contains the OST, pre-reformer and reformer monolith beds developed and tested at PSU. Integrated prototype system tests will cover the sequence of tests listed in the below table.

LFPPR Integrated Prototype System Tests

Test	Purpose
Baseline Operation	Prove viable operation at standard conditions
Load Variation	Establish performance as load is varied
Startup/Shutdown	Characterize transients and problem characteristics
Longevity Tests	Determine durability and performance over longer term operation
Environmental Tests	Check operation under cold and hot conditions
Fuel Flexibility	Determine impacts of fuel variations

At the conclusion of this task, a summary of performance results, covering fractionator/micro-burner, OST desulfurizer, pre-reformer and reformer test results will be prepared for review. These results will include information on output, load following, thermal and visual and acoustic signature, reliability, safety, and ease of operation. The results will then be compared with the LFPPR goals and specifications. Altex, Penn State, SOFC developer and DARPA personnel will meet to review results. Based on the review, the team will conclude on the viability of the LFPPR, when integrated with a SOFC, to meet the needs of the Palm Power program. If the LFPPR has the needed potential, work will be initiated on LFPPR Microreactor design.

5.4. TASK4-DESIGN, FABRICATE AND TEST MICROREACTOR

Under this task, the LFPPR system design prepared in Task 2 will be refined. Design procedures utilized under Task 2 will also be followed in this task. At this point SOFC process data will be included in the overall design. During the design process, the fabricator, Compatible Manufacturing, will be consulted to enhance the manufacturability of the final LFPRR design. Once the LFPPR design is completed, a Fault Tree/Failure Mode Analysis of the integrated system will be generated to evaluate product safety considerations prior to fabricating the system. Results will be reviewed and prioritized, and the design updated to minimize risk. Recommended design refinements will then be reviewed by the SOFC developer and DARPA. Inputs from the SOFC contractor will then be incorporated into the design and reviewed with DARPA. Upon design approval by the SOFC contractor and DARPA, the refinements will be implemented and fabrication will be initiated.

Compatible Manufacturing Incorporated will fabricate metal parts. The substrates and catalysts will be fabricated by PSU. Altex will fabricate ceramic wick and screen components and assemble all components, including the SOFC, in preparation for needed testing. The completed LFPPR/SOFC system will then be installed in the Altex SCET and instrumented. The instrumentation will follow that used in the prototype tests

Microreactor tests will follow those carried out in prototype testing and listed in the table above. Once the Altex tests are concluded, the unit will be shipped to the SOFC contractor for further testing that will focus on the SOFC. Also, following SOFC contractor testing it is anticipated that DARPA will identify a military service group that will carry out brief field testing of the unit as a simple battery charger.

5.5. TASK5-EVALUATE SYSTEM

Based on the Microreactor test results, as well as prior prototype test results and analyses, Altex, PSU and the SOFC contractor will determine how well the LFPPR has met Palm Power goals, as integrated with a SOFC. In addition, Altex will obtain information on other FC technologies from DARPA and a brief assessment of how the LFPPR could support these technologies will be prepared. The actual LFPPR/SOFC performance and expected alternative LFPPR/FC performance will then be compared to the performance of other power systems, and the advantages of the LFPPR approach identified. These evaluations and results will then be reviewed with DARPA to assess the viability of the LFPPR with selected FC systems. DARPA will then reach a conclusion on the viability of the LFPPR for Palm Power applications.

Progress and final reports will be prepared under this task. At the end of this task, a brief systems development and test plan will also be prepared.

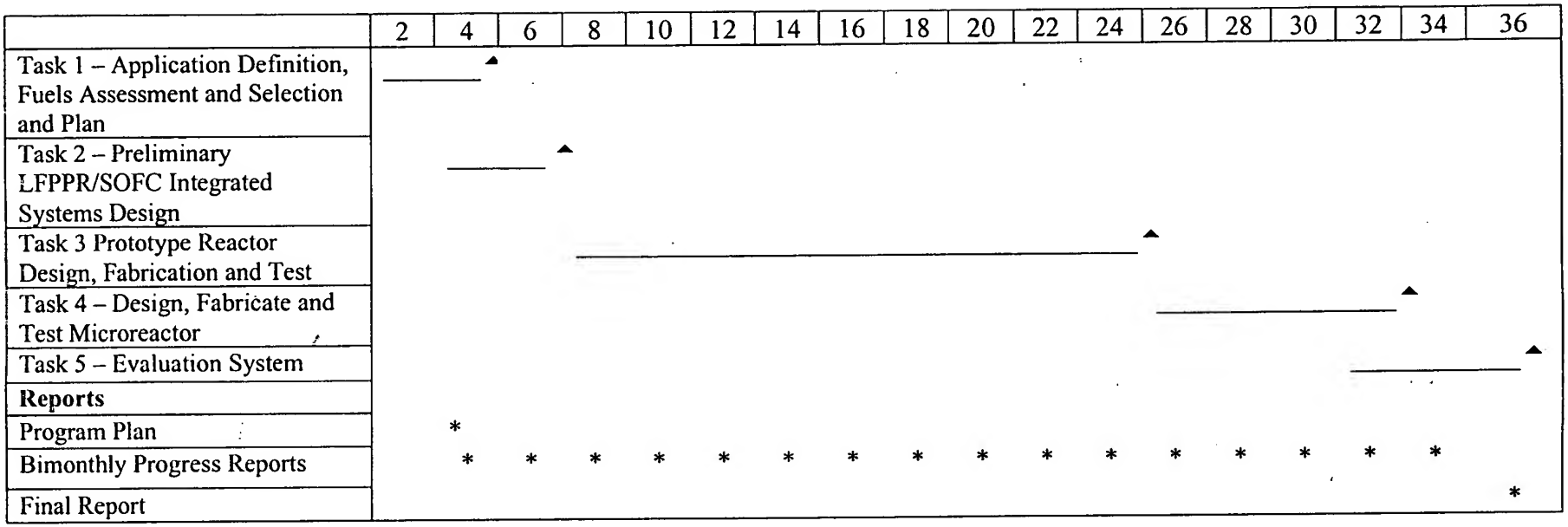
5.6 SCHEDULE AND MILESTONES

Figure 15 presents the schedule for the project. As shown, Tasks 1, 2, 3, 4, and 5 are completed 4, 6, 24, 32 and 36 months after project start. As shown in Figure 15, bimonthly reports are submitted throughout the length of the program. Also, at the end of the effort, a draft final report is submitted, followed by the final report, after DARPA review comments have been incorporated into the report. Important project milestones are listed in Table 9. These milestones will be used to monitor project progress towards the overall project goal.

Table 9 - LFPPR Project Milestones

	Months
• Team and DARPA meet on performance goals, plans and chose Fuel Cell Contractor	1
• Altex meets with Fuel Cell contractor	2
• Project plan prepared	2
• Fuel tests completed	3
• LFPPR Goals and Specs are Updated	4
• Refine LFPPR design to meet updated goals	5
• Program participants review and approve first complete LFPPR design	6
• Review complete design with DARPA	6
• Review LFPPR Prototype design with DARPA	7
• Prototype Micro-burner/fractionator at Altex fabricated	10
• Prototype Organic Sulfur Trap (OST) component fabricated	10
• Prototype Pre-reformer component fabricated	12
• Prototype Reformer component fabricated	15
• OST component tests completed	15
• Pre-reformer component tests completed	16
• Reformer component tests completed	19
• Integrated prototype fabricated	20
• Integrated Prototype tests completed	24
• Program participants and DARPA evaluate LFPPR performance and recommend project work to continue	25
• Design LFPPR Micro Reformer	25
• Prepare Tree/Failure Mode analysis	25
• Final Prototype LFPPR Micro Reformer design review by DARPA	26
• Micro-LFPPR Fabricated	28
• Micro LFPPR tests complete	31
• LFPPR performance reviewed with DARPA	31
• Fuel Cell contractor delivers Fuel Cell	31
• Micro-reformer integrated with FC tests completed	32
• System performance reviewed with DARPA	35
• Prepare draft final report for DARPA	36

Figure 15 - LFPPR Proposed Program Schedule



6.0 TEAM MEMBERS AND MANAGEMENT PLAN

Team members and their responsibilities are highlighted in Table 2. Altex is the lead organization and is responsible for developing and testing the integrated system. PSU will provide science and technology development for key subsystems. Compatible Manufacturing, Inc. will provide miniaturization and manufacturing expertise. As highlighted earlier, a SOFC Developer will be selected by DARPA after the program award. Altex, with the support of DARPA, then plans to work cooperatively with the contractor chosen by DARPA to ultimately produce and test an integrated LFPPR and SOFC under this project. This contractor would become a key team member for this project.

Altex will be responsible for all the tasks and subtasks, except Subtasks 3.2, 3.3. and 3.4, that involves OST, pre-former and reformer development. PSU will be responsible for these tasks. Compatible Manufacturing, Inc., that is a precision prototype manufacturer of complex equipment for the laser, medical and semiconductor industries, will manufacture the micro reactor in Task 4 and support prototype component design and manufacturing under Task 3. They have in-house manufacturing engineering support with workstation and software capability to manipulate CAD/CAM formats to drive their CNC machines. Their experience at producing small equipment for the laser, medical and semiconductor industries will be usefully applied under the proposed project.

The progress of the proposed program will be monitored by Altex management tools. Altex will work closely with other team members to plan and execute the program. At the initiation of the effort, a project plan will be produced by Altex and submitted to DARPA for review, comment, and for internal use to monitor program progress. Project activities will be planned and critical milestones defined over the length of the project, to ensure that the project is completed within schedule and budget, while meeting all technical objectives. Each critical milestone will be assigned a budgetary dollar value at completion and used to quantify program progress. Critical milestones are defined as those which are significant to meeting the objectives of the project, which have timescales of one month or greater in duration and cost greater than a few thousand dollars. These criteria will ensure that the milestones are at the proper level of visibility for monitoring program progress. The project plan, which includes the program statement-of-work, schedule, milestones and budget will then be produced and submitted to DARPA.

Once the program begins, labor, material, and service charges made to the project will be reported in an Altex weekly project status report. These reports will be internally reviewed weekly to ensure that proper labor, material, and service charges have been made to the project. The overall expenditures will be plotted and compared to the budget on a weekly basis. Project status and plans will be reviewed with staff on a weekly basis to determine technical progress and any problems that arise. For small problems, corrective actions will be recommended. For major problems, meetings to resolve the problems will be convened. At the conclusion of these meetings, plans and action items for the next weeks' effort will be defined. Activities which involve both Altex, SOFC contractor, Compatible Manufacturing and equipment supplier staff will be coordinated, as needed by the managers.

On a monthly basis, the list of project milestones will be reviewed and the value of the completed milestones will be defined. This value will then be compared to the value of the milestones scheduled up until that time and the schedule variances will be defined. The value of the completed milestones will also be compared to the budgeted value of the milestones to define

the cost variances. Theses variances will be defined to control variances to within 15 percent. If variances persist, plan revisions will be recommended to DARPA for review and approval.

Through telephone contact, the DARPA project manager will be apprised of project progress, problems and plans on a weekly basis. Also progress and problems will be documented in bimonthly progress reports. In addition, the project will be reviewed in-depth with DARPA on a regular basis as per the milestones list.

7.0 PRIOR EFFORTS

Altex and PSU prior efforts together support the activities needed under this project. PSU is providing science and technology on desulfurization and reforming. Several of their prior efforts support the current project. The Penn State fuel processing team, led by Prof. Chunshan Song, has been working through joint research projects with Air Products and Chemicals on steam reforming of natural gas for syngas and hydrogen production. The team has been addressing carbon formation issues through funded project with U.S. DOE on tri-reforming of natural gas, through funded projects with the U.S. Air Force (US DOD) and with U.S. DOE on catalytic fuel deep desulfurization of jet fuels (JP-8) and diesel fuels. The group has also done detailed chemical analysis of many different JP-8 type logistic fuels produced from different manufacturers and from different feed-stocks.

The following projects at PSU will directly contribute to the development of LFPPR.

1. Catalytic Oxidative Steam Reforming of Methanol for Fuel Cell Systems - DOE
2. Deep Desulfurization of Diesel Fuels by a Novel Integrated Approach - DOE
3. An Innovative Concept for CO_2-Based Tri-generation of Fuels, Chemicals and Electricity Using Flue Gas in Vision 21 Plant - DOE
4. Dynamic Characterization of Carbon Deposition during Steam Reforming of Methane in the Presence of Impurities.-Air Products and Chemicals Inc. (SAMCOM)
5. Catalysis for Methanol Reforming for Fuel Cell Applications. Du Pont
6. Steam Requirement and Carbon Deposition during High-Pressure Steam Reforming of Methane over Ni-Based Catalysts.-Air Products and Chemicals Inc. (SAMCOM)
7. Novel Supported Bimetallic Carbides for Coprocessing,-DOE Joint with Virginia Tech
8. High-Pressure CO_2 Reforming of CH_4 Using Supported Ni and Rh Catalysts for Syngas Production -Air Products and Chemicals Inc. (SAMCOM)
9. Advanced Thermally Stable Jet Fuels- US Air Force with Prof. Harold Schobert of PSU
10. Novel Bimetallic Catalysts from Organometallic Precursors. -U.S. DOE/FETC
11. Shape-Selective Alkylation over Molecular Sieve Catalysts.- BP Amoco

Altex is high technology engineering services firm that has developed a wide range of technologies. Related to this project, Altex has developed a low NOx burner that uses partial oxidation reforming. To control NOx, fuel was partially reformed to produce CO and hydrogen, to minimize prompt NOx, that is produced when CH radicals are present. Altex's ability to successfully develop innovative burner and other products stems from the considerable fundamental knowledge that has been gained by Altex from a decade of collaborative work with the Sandia National Laboratories, Combustion Research Facilities. These efforts were conducted in collaboration with MIT, Caltech, Gaz De France and Sandia scientific staff. Under Gas Research Institute (GRI) support, high-powered laser diagnostics were used to image fuel, CH, OH, NO species and temperature and combinations of the above on practical type flames. In addition, detailed combustion models were developed, including vortex dynamics models where the development of turbulence was directly modeled. This unique experimental and modeling information has provided new insights into flames and combustion emissions. This information

has been successfully used by Altex to develop a low NOx burner for firetube boilers, that is being commercialized by Gordon-Piatt, a major manufacturer of burners for firetube boilers. These fundamental experimental and modeling insights gained at Sandia, will be very useful in the LFPPR effort.

Altex staff are also experienced with monolithic based catalytic reactors. As part of a major effort for the EPA, Altex staff developed heterogeneous surface and homogeneous gas-phase kinetic reaction models that could predict the combustion of fuels in honeycomb monolithic reactors. The models included convective heat and mass transfer, radiative heat transfer and general kinetic reaction schemes (up to 300 reactions) to cover catalytic combustion blowout, heat release and emissions (NO, NO_2, CO), unburned hydrocarbon) performance. This model can be directly applied in support of the proposed project.

Altex has worked closely with many well-known heating system manufacturers, such as Rheem, American Water Heater Products, A.O. Smith, Nieco, Eclipse Combustion, Cleaver Brooks, Gordon-Piatt Energy Group, as well as Mountain Safety Research (MSR) in the camping equipment field. Development and commercialization experience with these manufacturers is directly relevant to the proposed effort.

Currently, Altex is developing and testing the Low Cost Pocket Stove (LCPS) for the Army (Natick). This stove utilized a 600w burner that reliably burns diesel, JP8, kerosene and even white gas fuel. A critical need of this development was to be able to operate the burner long term on diesel fuel without pluggage or fall off in output. Conventional burners of larger scale of 3000 w capacity will only operate for 20 hours without plugging. When these burners are scaled down, orifice sizes are reduced and pluggage occurs even more quickly. The other challenge with diesel or JP8 fuel with is the high soot production and flame luminosity, and flame signature that is undesirable for military use. Altex addressed these dual challenges by developing the Porous Surface Element (PSE) special wick and perforated metal screen burner. The novel approach has been tested long term using an automated combustion test cycle apparatus at Altex.

Through our experiences in burner, pollution control and fuel handling and equipment development, and work with manufacturers, such as Nieco, MSR, Alzeta, Riley Stoker, Gordon-Piatt, and Eclipse, Altex has acquired the capability to translate concepts into commercial products. Also, as a technology developer, we keep abreast of developments of other researchers, developers and manufacturers in this area. In conclusion, Altex has extensive direct and indirect experience that will make the program a success.

8.0 FACILITIES

ALTEX

Altex has over 4500 square ft of facility space, covering office spaces, fabrication shops and test facilities. Of this, 2000 square ft space is dedicated to various combustion and fuel test facilities. The Altex Small Combustion Equipment Test Station (SCETS) occupies a portion of this facility. The SCETS facility is equipped with standard temperature and flow monitoring instrumentation. The facility is also equipped with standard emission monitors. A data acquisition system is available which collects and stores the data. This facility has all the necessary equipment for the fuel testing, and development of the micro-burner and the fractionator portion of the LFPPR, that take place during the first half of the program. During this period, PSU will be developing the other components. As these components become available, they will be shipped to Altex for prototype testing. For these tests, that are planned to take place in the second half of the program , Altex will purchase a GC on a cost share basis to

upgrade the test facility. With this additional analytical tool, all the necessary diagnostics are available to complete the project.

The SCETS facility has been used in the past to develop and test small diesel and JP8 fueled burners, water heaters, meat broilers, radiant burners and forced air burners. In addition to SCETS, Altex has available an automated longevity apparatus that has been used to test the ability of small-scale diesel fuel burners to operate over many start and stop cycles without degradation in output. The facility has built in safety features for unattended operation, and will be utilized to test the durability of the LFPPR over long term operating cycles.

The Altex shop will be used for quick turnaround fabrication and modifications of the LFPPR prototypes during testing. For more major modifications, Compatible Manufacturing, Inc. will be utilized. The Altex Technologies Corporation microcomputers will be used for the needed thermal, flow and combustion modeling, project tracking, and producing the needed reports.

PENN STATE UNIVERSITY

PSU has a wide range of laboratory-scale reactor, analytical and computational facilities. Access to the full Materials Characterization Laboratory, which houses state-of-the-art spectroscopic facilities, and to the Materials Research Laboratory, which provides XRD and many other spectroscopic techniques, and to the faculty members in several related departments, add to the capability of PSU team to meet the LFPPR research needs.

Laboratory reactors include: atmospheric-pressure fixed-bed gas-phase flow reactor; fixed-bed gas-phase flow reactor; high-pressure fixed-bed liquid-phase flow reactor; 300 mL and 1000 mL stirred-tank autoclave reactors; 25 mL-80 mL batch micro-reactors; capable of high pressure; Teflon-lined reactors and special ovens for synthesis of zeolite catalysts; 1000 mL multi-stage continuous flow stirred-tank reactor capable of high temperature and high-pressure operations.

Analytical facilities include: Tapered-Element Oscillating Microscope (TEOM) for dynamic characterization of carbon formation or weight change of catalysts under flow reaction conditions, High-temperature/High-Pressure CIR FT-IR System for catalyst characterization, Pulse Chemisorption and TPD apparatus for catalyst characterization ,Thermogravimetric Analyzer (TGA) coupled with Differential Scanning Calorimeter (DSC), Gas Chromatography-Mass Spectrometry (GC-MS), capillary GCs with FID and TCD, capillary GC with sulfur-specific FPD, 2D-High Performance Liquid Chromatography (HPLC) with PDD, high-temperature simulated distillation GC, solid-state nuclear magnetic resonance (CPMAS NMR) and Liquid-state NMR.

Computational facilities include: Silicon Graphics Computers , Molecular Simulations Inc. softwares for catalyst research, CAChe software for computational analysis of catalysts, MOPAC software for quantum chemical analysis of chemical reactions, 3-D modeling and visualization software for molecules and chemical reactions.

COMPATIBLE MANUFACTURING INC.

Compatible Manufacturing, Inc., located in the heart of Silicon Valley is a quick turnaround prototype and short run production manufacturer for the laser, medical and semiconductor industries of the valley. They can produce high tolerance, small-scale equipment using CNC based machines. They have in-house manufacturing engineering support that will assist Altex in producing LFPPR designs that can be easily manufactured as well as being durable. They can design and prepare any needed soft tooling to fabricate special parts, and will provide on-site quality control inspections in a climate controlled room using an extensive line of

gages and precision measuring equipment. They currently have a 10,000 square foot facility with 8,000 square feet of manufacturing floor space. Pentium III workstations are used to manipulate design files and create files to drive the CNC machines. Equipment consists of 12 CNC milling machines, 9 with 4 axis capability, 7 turning machines, 5 with CNC capability and miscellaneous grinders, saws, etc. Given their experience with fabricating small systems for the high tech industries in Silicon Valley, it is anticipated that they will effectively support the design and manufacture of small LFPPR systems under the proposed effort

9.0 KEY PERSONNEL

Dr. Mehdi Namazian will lead this program. Dr. Namazian has over 20 years of experience in fuels and combustion research, including 10 years of collaborative turbulent gas flame research at Sandia National Laboratories, Combustion Research Facility. During this effort, he led a multi tasks, multi participants collaborative program with MIT, Caltech, Gaz De France and Sandia National Laboratories. Under this program high power laser diagnostics, and sophisticated modeling tools were used to characterize a prototype burner, and extend the results to full scale. Diagnostics included LDV for velocity, Mie scatering for overall flow characterization, Rayleigh for temperature, Raman for fuel , CH and OH fluorescence for flame front and combustion characterization and NO fluorescence for pollution production characterization. These experimental tools were combined with MIT's vortex dynamics flow modeling and Altex Flame Chemical Analysis model. In addition to over 25 scientific publications, models and data bases, this program led to the development of two low NOx burners at Altex. This unique experience will be used on this program. Besides this fundamental combustion experience, Dr. Namazian has performed applied research on gas burners for boilers and gas turbine and diesel engines. At Altex, as the technical leader and Project Engineer on the LCPS program, he has considerable experience with liquid logistic fuel handling and utilization. This experience is directly relevant to the LFPPR program. He has a Ph.D. in engineering and has written over 50 articles on combustion. He is holder of three U.S. patents.

Dr. John T. Kelly, will assist in executing this program. He will use his expertise in catalytic combustion and catalytic reactor modeling to lead the efforts in Task 3. Results of the PROF-HET model were highlighted in Figures 10 and 11. Dr. Kelly has over 25 years of experience in burner development programs for pollution control. Of direct relevance to the project is his role as the Principal Investigator on the LCPS, that burned diesel fuel at the 600w scale. As noted in Section 2, this burner has special nonplugging characteristics that are attractive to apply under the proposed effort. In addition to this work, he has led several projects to develop low emissions burners for steel furnaces, firetube boilers, and watertube boilers. His experience in leading combustion research and development efforts, in support of burner developments, is a very valuable asset to the program. In addition to burner development work, Dr. Kelly has collaborated with Sandia National Laboratories, Combustion Research Facility staff on turbulent flame research. As part of that effort, computer models were developed that could predict emissions from practical burner flames. This unique experience will be applied in the program. Dr. Kelly has a PhD in engineering and has written over 50 articles on combustion. His resume is attached in Appendix A

Robert Nickeson will also participate in this program. He has been a key contributor in developing and testing the LCPS and other small burners, and was the Principal Investigator on the water heater burner development work. In addition to small burner design and development, he has been a technical contributor to several industrial burner and process system research and development programs. In the course of these programs he has interacted with product

manufacturers, and is aware of the importance of incorporating commercial product requirements into burner development designs. This combined experience will ensure a successful LFPPR program. Mr. Nickeson has an MS degree in engineering.

Professor Song will lead the PSU efforts. He is the program coordinator of the Energy Institute (EI) at PSU. He has directed the Applied Catalysis in Energy Laboratory (ACEL) at PSU. ACEL is one of the research centers of the EI, with focus on catalysis and reaction chemistry. Prof. Song is leading a research team on steam reforming of natural gas for syngas and hydrogen production. He has been addressing carbon formation issues through funded project with U.S. DOE on tri-reforming of natural gas, through funded projects with U.S. Air Force (US DOD) and with U.S. DOE on fuel catalytic deep desulfurization of jet (JP-8) and diesel fuels. Prof. Song and his research group have extensive research experience on steam reforming and oxidative steam reforming of natural gas and on catalytic processing of liquid fuels.

Prof. Song is serving as a co-chair for an American Chemical Society Symposium on "Catalysis for Fuel Cells and Fuel Processing" to be held at ACS National Meeting in Chicago during August 26-31, 2001. He has also served as a co-chair for several international symposia on catalytic processing of liquid fuels, such as the ACS Symposium on "Catalysis in Fuel Processing for Environmental Protection" during September 7-11, 1997, and at the ACS National Meeting in Las Vegas, and the ACS Symposium on "Chemistry of Diesel Fuels" at the ACS National Meeting in Boston during August 25-30, 1998.

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Dr. John T. Kelly, President of Altex Technologies Corporation, Santa Clara, California

Experience:

1985 -- Present: Responsible for the management of a research organization with a focus on combustion and pollution control. Managed and was principal investigator on several combustion and pollution control projects for Gas Research Institute, Environmental Protection Agency, Department of Energy, Electric Power Research Institute, NASA and commercial clients with a total contract value over $15 million dollars. Managed and supported the design, construction and operation of small-scale and pilot-scale test facilities. Researched and developed several low emissions burners. Defined and helped develop computer models for limestone calcination and SO_2 sorption, NOx formation (thermal, prompt and fuel NOx) and reduction, coal devolatization and char combustion, furnace heat transfer and burner combustion stability.

1974 -- 1985: Acurex Corporation; Mountain View, California
Program Manager -- Responsible for managing $1,000,000 per year of combustion research programs. Applied novel detailed optical diagnostics to nonpremixed bluff-body gas flames. Developed, through pilot-scale tests, a combustion modification technique for pollution control, which is presently installed on large utility boilers. Executed a fundamental research program to develop a novel combustion modification technique for pollution control, which is now receiving international and national attention.
Section Leader -- Responsible for leading the Combustion Technology Section consisting of nine engineers and two chemists (PhD, MS, BS in ME, ChE, fuel science, and chemistry). Acted as key project scientist.
Staff Engineer -- Developed and applied complex computer codes to chemically reacting flow problems and led pilot and subscale combustion experiments.

1972 -- 1974: Aerochem Research Laboratories; Princeton, NJ
Research Engineer -- Directed engineers and computer programmers in developing complex computer models. Developed sophisticated computer models of rocket exhaust plumes, re-entry vehicle plasma sheaths and re-entry vehicle dynamics.

Education:

1967-1972 Polytechnic Institute of New York, New York City, NY,
PhD, Aeronautics and Astronautics
1966-1967 Massachusetts Institute of Technology, Cambridge,
Massachusetts, MS, Nuclear Engineering
1962-1966 The Cooper Union, New York City, New York, BS, Mechanical
Engineering

Publications: Author or co-author on over fifty technical publications.

SELECTED PUBLICATIONS OF DR. JOHN T. KELLY

1. "Premixed one-dimensional flame (PROF) code user's manual" -- with R.M. Kendall, Acurex Final Report FR/78-277. (1978)
2. "Fuel Staging for Pulverized Coal Furnace NOx Control" with Pam, R.L., and Suttman, S.T., Proceedings of the 1982 Joint Symposium on Stationary Combustion NOx Control,
3. "Fuel Component Impacts on Fuel Staging NOx Control," with -- S.T. Suttman, American Flame Research Committee Meeting, Newport Beach (1982).
4. "Low-NOx Tangential System SOx control Through Sorbent Injection," --with Ohmine, S., Chu, E.K., and Martin, R. J., Proceedings of the 1982 Joint Symposium on Stationary Combination NOx Control, November 1-4, 1982
5. "Pilot -Scale Characterization of a Dry-Calcium-Based Sorbent Fired System," --with Ohmine, S. and Martin, R., Proceedings of the First Joint Symposium on Dry SO2 and Simultaneous SOx/NOx Control Technologies, November 13-16, 1984, San Diego, California
6. "Flow and Combustion in Bluff-Body Stabilized Flames," -- with M. Namazian, R. Schefer, and S. Johnston, Central/Western States Section, The Combustion Institute Meeting Paper No. 2-1B, San Antonio, TX April 22-23, 1985.
7. "Velocity Measurements in Turbulent Nonpremixed Bluff-Body Stabilized Flame," -- with R.W. Schefer and M. Namazian, Combustion Science Tech., 4-6, 101, 1987
8. "Scalar Dissipation Measurements in the Developing Region of a Jet," -- with M. Namazian and R.W. Schefer, Combust. Flame, accepted (1987)
9. "Nonpremixed Bluff-Body Burner Flow and Flame Imaging Study," -- with M. Namazian and R.W. Schefer, Experimental Fluids, submitted 1987.
10. "Near Field Instantaneous Flame and Fuel Concentration Structure," -- with M. Namazian and R.W. Schefer, Twenty-Second Symp. (International) on Combustion, (1988)
11. "Structural Characteristics of Lifted Turbulent-Jet Flames," -- with R.W. Schefer and M. Namazian, Twenty-Second Symposium (International) on Combustion, (1988).
12. "Comparison of Turbulent-Jet and Bluff-Body Flames, " -- with R.W. Schefer and M. Namazian, Combustion Science Tech., 88-03-09, 1988
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Dr. Mehdi Namazian

Experience:

1985 to Present - Altex Technologies Corporation
Vice President and Principal Scientist- Responsible for the company's operation and projects executions. Responsibilities include program management, technical direction, staff development, planning, financial management and project execution. Principal Investigator on several programs including low NOx burner developments for EPA. Directed and coordinated a collaborative research and development effort with MIT, CalTech, Gaz De France and Sandia National Laboratories, Combustion Facilities. Technical leader on the development of a pocket stove for army operating on logistic fuels.
1984 to 1994 - Visiting Scientist, Sandia National Laboratory, Combustion Research Facility, Livermore, California
Coordinated a multi-task program and developed and applied advanced laser diagnostics to jet and bluff-body burners to understand turbulent mixing, flame structure and pollution formation. These measurements have led to a greater understanding of non-premixed jet and bluff-body burner flame processes and have led to the development of two patented Low-NOx burners.
1984 to 1985 - Staff Engineer, Acurex Corporation, Mountain View, California
Planned and performed experiments on turbulent combustion processes in nozzle mixed flames. Different types of conventional nozzle mixed burners were studied to characterize mixing and combustion.
1984 to 1981 - Assistant Research Engineer, Mech. Eng. Dept. of UC Berkeley, Ca.
Working with Lawrence Berkeley Laboratories researchers, planned and performed laser diagnostics based experiments on premixed flame burners, simulating afterburners. Analyzed data to study the structure of the flame and, from the analysis developed a flame model. Performed diesel engine tests using diesel fuel, coal/water, and coal/diesel slurry as fuel.
Awards and Honors:
Arch T. Colwell Merit Award from Society of Automotive Engineers
Program Committee member of International Symposium on Combustion, 1990 - present.
Societies
Combustion Institute, American Society of Mechanical Engineers, American Institute of Aeronautics and Astronautics
Education
Massachusetts Institute of Technology, Cambridge, MA. PhD in Mechanical Engineering, June 1981.
Massachusetts Institute of Technology, Cambridge, MA. Master of Science, completed July, 1977.

Publications
Published over 50 documents with over 25 in referred journals.

SELECTED PUBLICATIONS OF DR. MEHDI NAMAZIAN

1. Namazian, Nickeson, Paz, Kelly, "Low Cost Pocket Stove Operating on Military Logistic Fuels", Progress Report, US Army Solider Command, DAAD-99-C1021, Dec 2000.
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13. Schefer, R.W., Namazian, M. and Kelly, J., "Velocity Measurements in a Turbulent Nonpremixed Bluff-Body Stabilized Flame", Combustion Science Technology, 56, 4-6, 101 (1987)
14. Namazian, M., Robben, F., Talbot, L., "Density Fluctuations in Premixed Turbulent Flames", Twentieth Symposium (International) on Combustion/Combustion Institute, 1984.

Key Personnel at PSU

Chunshan SONG
Pennsylvania State University, 206 Hosler Building, University Park, PA 16802
Tel: 814-863-4466 / **Fax**: 814-865-3248 / **E-mail**: csong@psu.edu

WORK EXPERIENCE

2000-Present **Program Coordinator,** Clean Fuels and Catalysis, The Energy Institute, The Pennsylvania State University

1998-2000 **Director,** Applied Catalysis in Energy Laboratory, The Energy Institute, The Pennsylvania State University

1997-Present **Associate Professor** of Fuel Science, Department of Energy & Geo-Environmental Engineering, The Pennsylvania State University

1989-1997 **Assistant Professor** of Fuel Science (1994-1997) and Research Associate (1989-1994), Department of Materials Science & Engineering, Pennsylvania State University

1989-1989 **Research Associate**, Res. & Dev. Center, Osaka Gas Company, Osaka, Japan

RESEARCH AREAS:

Catalysis & Process Development for Fuel Processing & Environmental Protection
Shape-Selective Catalysis for Synthesis of Industrial Organic Chemicals
Synthesis & Applications of Catalytic Materials for Clean Fuels and Chemicals
N. Gas & CO_2 Conversion; Advanced Jet Fuels; Analytical Characterization

RESEARCH INTERESTS RELATED TO REFORMING, H_2 & FUEL CELLS

Steam Reforming and Oxidative Steam Reforming of Natural Gas, Methanol, Diesel Fuel and JP8 Jet Fuels as well as Gasoline; Carbon Formation during Hydrocarbon Reforming; Water-Gas-Shift; Diesel Fuel and Jet Fuel Desulfurization; Design & Application of Materials & Processes

Selected Publications

- C. Song. Catalytic Fuel Processing for Fuel Cell Applications. Challenges and Opportunities. Am. Chem. Soc. Div. Fuel Chem. Prep., **2001**, 46 (1-2), in press.
- C. Song. Tri-reforming: A New Process for Reducing CO2 Emissions. Chemical Innovation (formerly Chemtech, ACS), **2001**, 31 (1), 21-26.
- S. T. Srimat, W. Pan, C. Song, and J. N. Armor Dynamic Characterization of Carbon Formation during CO_2 Reforming and Steam Reforming of CH_4 Using Oscillating Microbalance. Am. Chem. Soc. Div. Petrol. Chem. Prep., **2001**, 46 (1-2), in press.
- C. Song, C. S. Hsu, and I. Mochida (Editors). Chemistry of Diesel Fuels. Taylor & Francis Publishing Company, New York, **2000**, 294 pp.
- C. Song, S. T. Srimat, L. Sun and J. N. Armor. Comparison of high-pressure and Atmospheric-pressure Reactions for CO_2 Reforming of CH_4 over Ni/Na-Y and Ni/Al_2O_3 Catalysts. Am. Chem. Soc. Div. Petrol. Chem. Prep., **2000**, 45 (1), 143-148.
- S. T. Srinivas, and C. Song. Effects of Pressure on CO_2 Reforming of CH_4 over Rh Catalysts. Am. Chem. Soc. Div. Petrol. Chem. Prep., **2000**, 45 (1), 153-156.
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Awards

- Wilson Award for Outstanding Research, Pennsylvania State University, 2000.
- Senior Technical Advisor to United Nations Development Program, 1999
- NEDO Fellowship Award, New Energy & Ind. Technol. Dev. Organization, Japan, 1998
- AIST Invitation Fellowship Award, Agency of Ind. Sci. & Technol. Japan, 1995

Education

- B.S., Chemical Engineering, Dalian University of Technology, Dalian, China, 1982
- M.S., Applied Chemistry, Osaka University, Osaka, Japan, 1986
- Ph.D., Applied Chemistry, Osaka University, Osaka, Japan, 1989

Logistic Fuel Preprocessor and Reformer for Fuel Cell Applications

Dr. Mehdi Namazian and Dr. John Kelly
Altex Technologies Corporation
650 Nuttman Rd.
Santa Clara, Ca. 95054

and

Professor Chunshan Song
Penn State University
University Park, PA 16802

for

DARPA Palm Power Kickoff Meeting

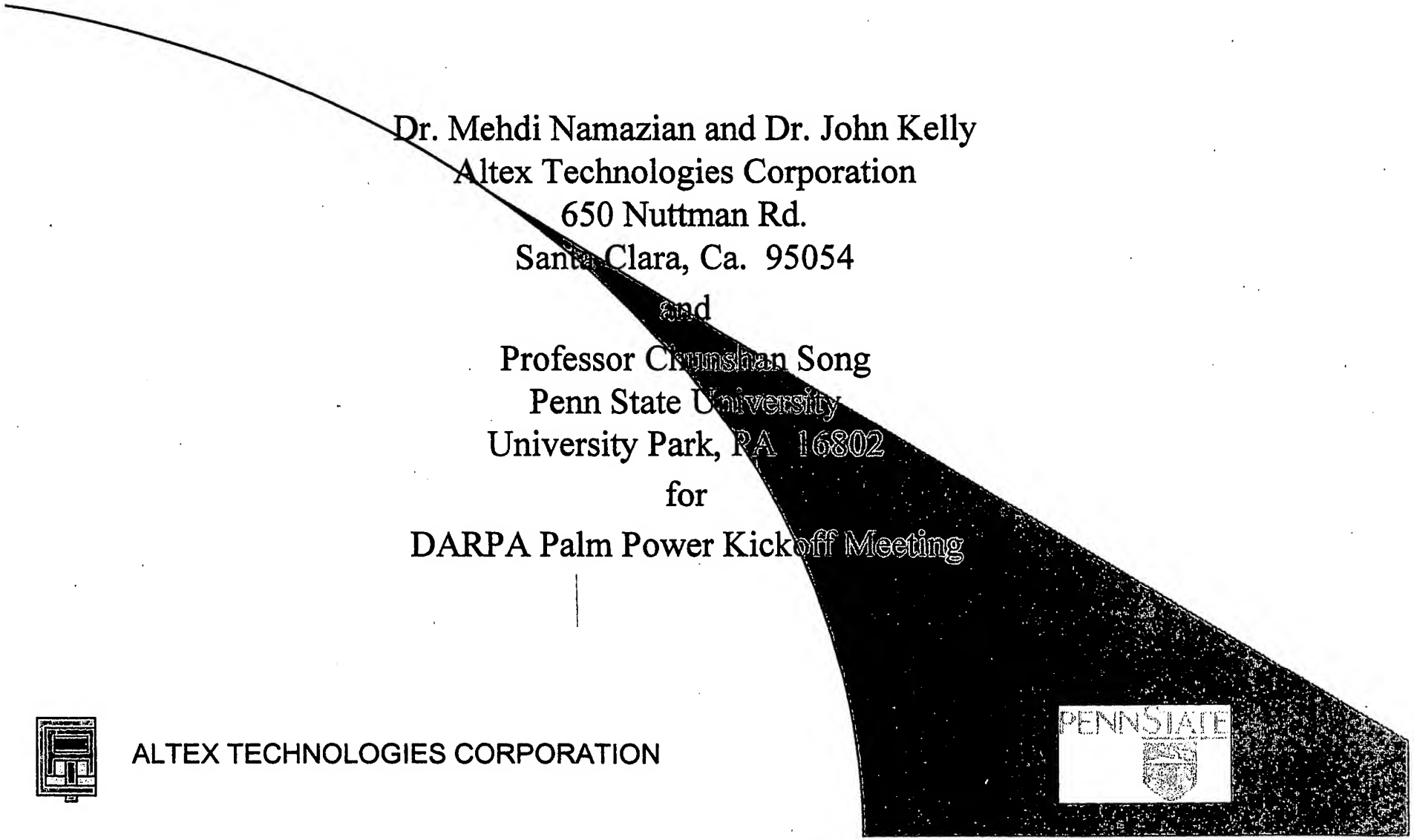

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Exhibit 4

Logistic Fuels Advantages and Challenges for Fuel Cell Applications

Advantages of JP8 and like fuels

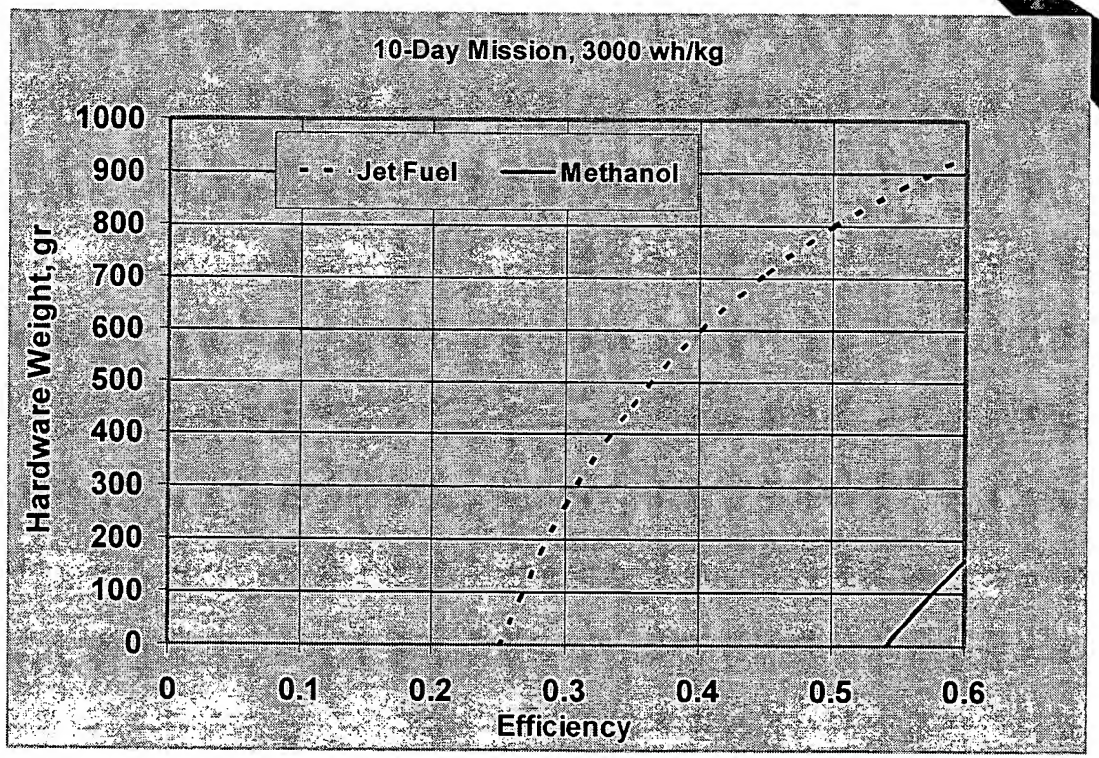
- Readily available
- Easily Transportable
- Safe
- High Energy content

Challenges of JP8 and like fuels

- Sulfur and contaminants poisons reformer and fuel cell
- High carbon formation potential that deactivates reformer elements

Logistic Fuel Advantages

- **JP8's high energy content makes it a better fuel choice for longer Palm Power missions**



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LFPPR Project Objective

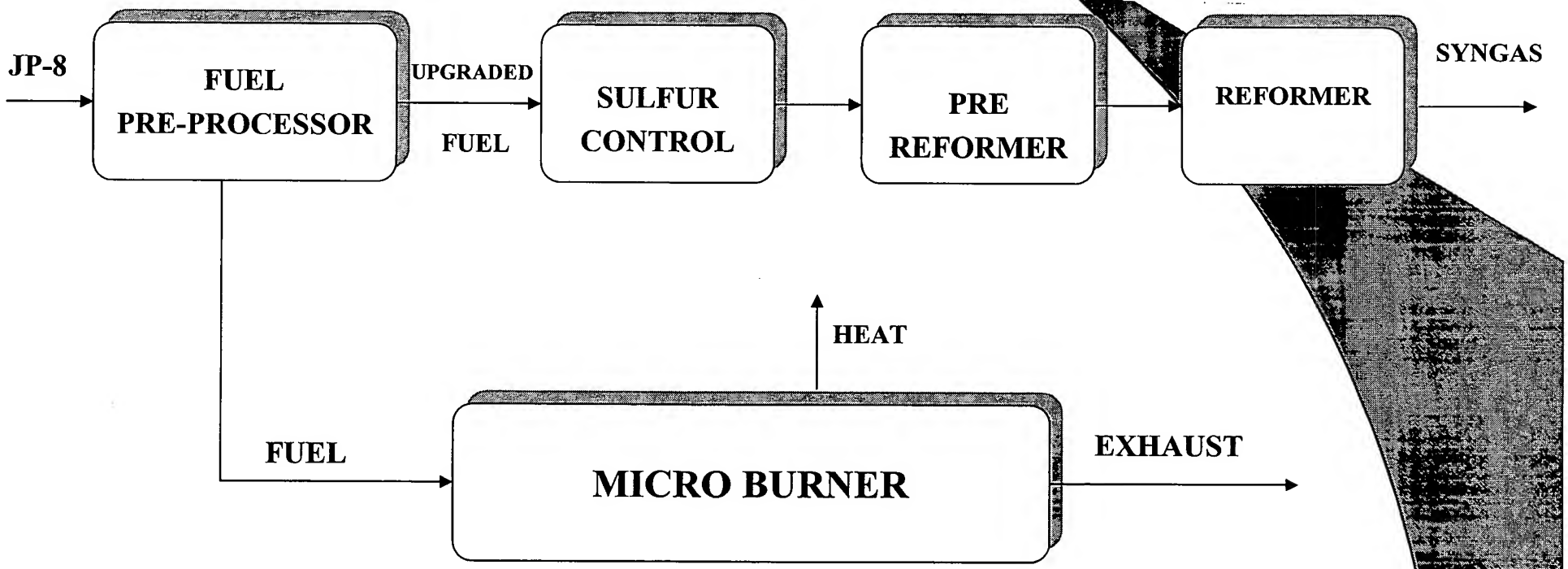
Develop and test a Logistic Fuel Preprocessor and Reformer (LFPPR) for Palm/Power 3-and 10-day missions

ALTEX TECHNOLOGIES CORPORATION

PENNSTATE

LFPPR Approach

- **Risk is managed by incorporating several sequential**

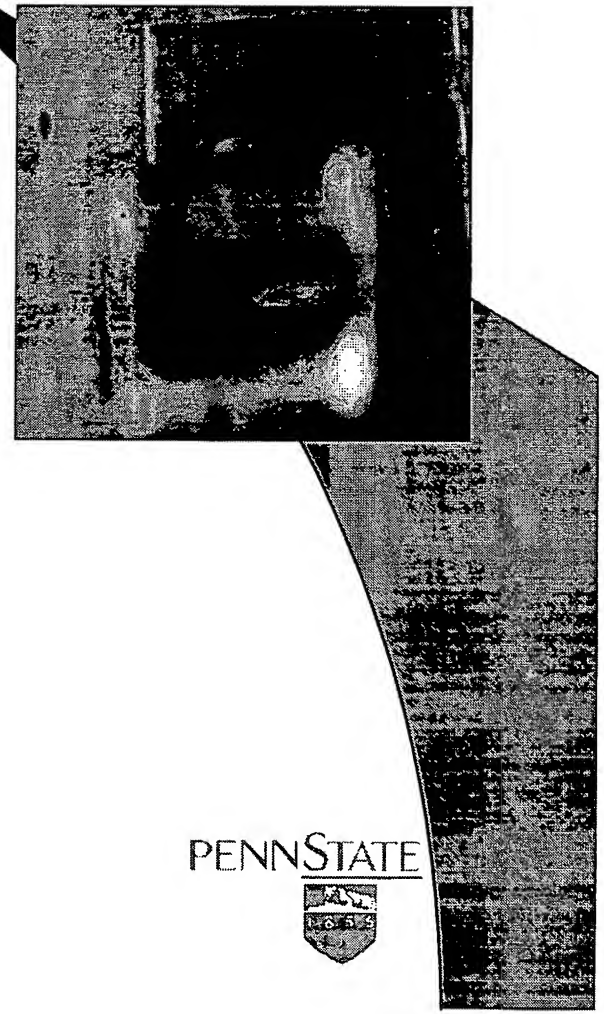


- System utilizes novel miniaturization techniques for heat source and reactors

PENNSTATE

Altex Logistic Fueled Micro Burner Experience

- **Burner is compact, lightweight and scaleable and operates cleanly with low luminosity flame**
- **Tested with diesel and JP8**
- **Tested from 0 to 50°C**
- **Tested over 800 Cycles of on-and off operation without performance degradation**
- **Tested in continuous mode for 120 hours without degradation**



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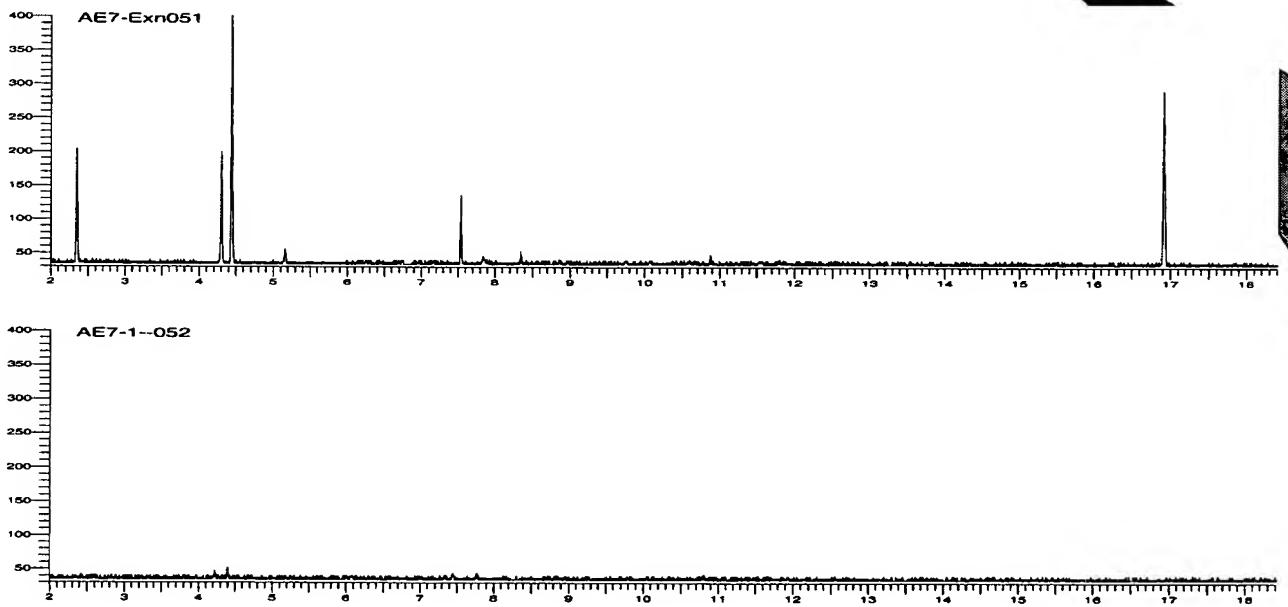
Pennsylvania State University Fuels Processing Experience

- Jet and diesel fuel catalytic processing
- Catalyst development for steam reforming
- Reforming and oxidative reforming of fuels
- Dynamic characterization of carbon deposition during steam reforming
- Deep desulfurization of liquid fuels

PENNSTATE

Pennsylvania State University
Sulfur Control

- **Sulfur control is proven on gasoline**



GC-FPD of gasoline before (top) and after sulfur removal

Project Plan

- Define fuel cell partner
- Collect fuel samples
- Test fuels
- Refine LFPPR design
- Fabricate and test LFPPR prototype components
    - Fuel Preprocessor/micro-burner
    - Sulfur removal module
    - Prereformer/Reformer module
- Fabricate and test integrated LFPPR prototype
- Refine design and fabricate refined LFPPR for integration with SOFC
- Test LFPPR and LFPPR/SOFC

Project Key Milestones and Deliverables

Milestone	Deliverable	Date
Prepare Project Plan	Plan	8/30/01
Fuel Tests Completed	Test Data	10/31/01
Review LFPPR Goals & Specs	Table of Goals and Specs	11/05/01
Screening Test Plan Review	Test Plan	11/05/01
Prepare LFPPR Preliminary Design and review	Design Package	1/30/02
LFPPR Test Plan Review	Test Plan	3/1/02
Design and test LFPPR components	Test Data	2/14/03
Test integrated components	Test Data	8/1/03
Review Prototype Performance	Performance Assessment Package	8/10/03
LFPPR Refined Design and Review	Refined Design Package	10/03/03
Refined LFPPR Test Plan Review	Test Plan	10/03/03
LFPPR Tests	Test Data	3/31/04
LFPPR and SOFC Tests	Test Data	4/30/04
LFPPR Performance and Cost Evaluation	Performance and Cost Assessment Package	6/30/04

SOFC Partner Need and Contact

- Seeking collaboration with SOFC developer
  - Need SOFC process conditions by end of this year
  - Need SOFC for integrated testing with LFPPR, 30 months into the project
- Contact Mehdi Namazian, mehdi@altextech.com (408) 982-2303

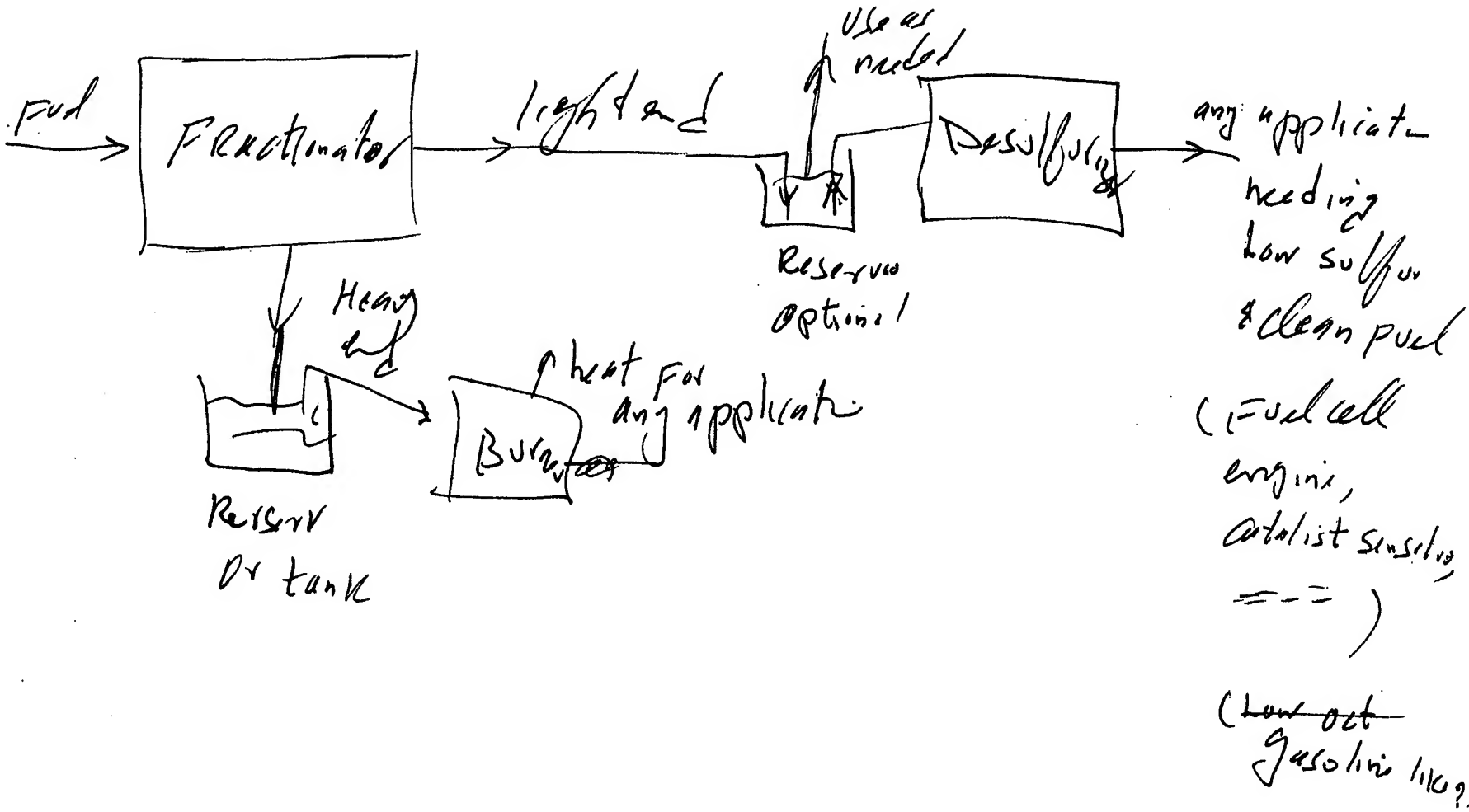

Fuel
Fractionator
light end
Use as needed
Desulfurizer
any application needing low sulfur & clean fuel
(Fuel cell engine, catalyst sensitive, ---)
(low oct Gasoline blend)
Reservoir optional
Heavy end
heat for any application
Burner
Reservoir or tank

Exhibit 5

Attachment 11

Inventions and Innovations Program

Solicitation Number DE-PS36-02GO90014

Executive Summary

Fuel Preprocessor (FPP) for a Solid Oxide Fuel Cell Auxiliary Power Unit

Altex Technologies Corporation
650 Nuttman Road, Suite 114
Santa Clara, CA 95054
Dr. Mehdi Namazian
Phone: 408-982-2303
Fax: 408-980-8611
Email: mehdi@altextech.com

15Congressional District

Abstract

Currently, trucks have to operate at idle to produce the needed heat and cooling for the driver's sleeper compartment. This results in $80x10^{12}$ Btu/year energy waste and costs the truck industry over one billion dollars per year in fuel cost alone. Realizing these enormous penalties, DOE has targeted the US truck fleet APU as a prime target to be converted to a SOFC. However, the development of a SOFC APU has been held back by the difficulty of reforming diesel fuel. The Fuel Preprocessor(FPP) proposed under this program, upgrades diesel fuel to a clean fuel so that it can be used in the SOFC APU systems at their current stage of developments. Although the FPP is initially targeted for this application, it is flexible and can be integrated with other fuel cell systems, to make them fuel flexible.

Under this project, the FPP design will be refined and a prototype FPP unit will be built and tested for a 5 Kwe SOFC/APU. Test results will be used to evaluate the system performance, cost and its impact on the transportation sector and other industries that fuel cell is rapidly penetrating into. Armed with this results, Altex will embark on the commercialization of the technology. FPP is projected to save 7800 billion Btu/year energy, save the truck industry 183 million dollar per year and annually reduce CO_2, NOx, and CO by 0.9 million tons, 6000 tons and 10080 tons, respectively. These savings will drive the FPP commercialization.

The FPP feasibility is shown and is presently in the Developmental stage

The FPP is targeting EERR/Transportation.

The data contained in pages2-10 of this application have been submitted in confidence and contain trade secrets or proprietary information, and such data shall be used or disclosed only for evaluation purposes, provided that if this applicant receives an award as a result of or in connection with the submission of this application, DOE shall have the right to use or disclose the data herein to the extent provided in the award. This restriction does not limit the government's right to use or disclose data obtained without restriction from any source, including the applicant.

Exhibit 6

1. Critical Review of Technology Status

1.1 Introduction

Conventional idling in trucks for generating auxiliary power consumes over 800 million gallons of diesel fuel per year. If instead, a fuel cell based APU were used, nearly $80x10^{12}$ Btu per year energy will be saved. This is a substantial energy savings. However, diesel fuel is a challenging fuel to use in fuel cells because it has heavy ends that can transform into carbon deposits and gums that can block passages and deactivate fuel reformer and fuel cell reactor elements. In addition to the heavy ends problem, diesel also contains sulfur compounds and inorganic contaminants that can poison fuel cell reactor elements. Therefore, the great promise of a fuel cell APU operating on diesel fuel is constrained by heavy ends and contaminants in diesel fuel.

1.2 Brief Description of the Fuel Preprocessor (FPP) Concept

Recognizing the challenges of utilizing diesel fuel in fuel cell based APU systems, Altex has identified the innovative Fuel Preprocessor (FPP) that will transform diesel fuel into a clean fuel for driving APU fuel cell systems. As shown in Figure 1, the FPP consists of a fuel fractionator that separates the fuel into light and heavy end fractions. This fractionation step is critical in that it separates out the problematic heavy ends, inorganic contaminants and a majority of the sulfur in the fuel and transports only light clean fuel to the fuel cell system. The problematic heavy end components are transported out of the fractionator, cooled down and returned back to the truck's fuel tank. The fuel that is returned to the tank constitutes less than 1% of the fuel tank capacity. This small amount of fuel has a negligible effect on the quality of the fuel present in the tank as compared to the fuel spec.

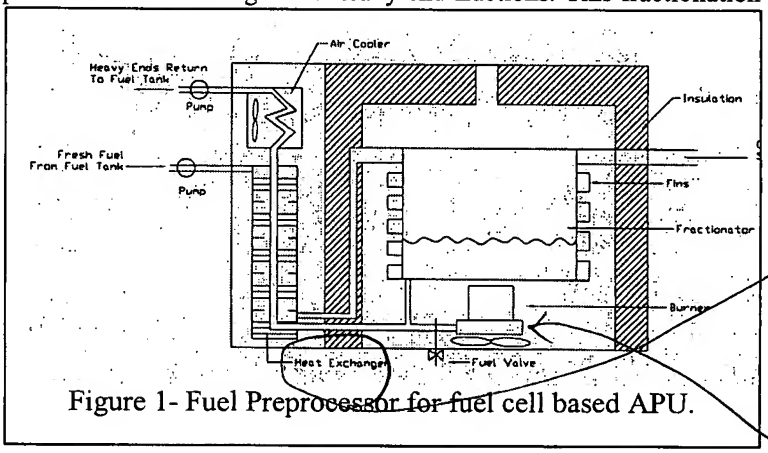


Figure 1- Fuel Preprocessor for fuel cell based APU.

The quality of the clean fuel that is sent to the fuel cell depends on the fractionator temperature. This temperature can be set as per needed fuel quality. For example, by setting the temperature at 200 C, which is the Final Boiling Point (FBP) of gasoline, the clean portion of the fuel will be similar to gasoline. By converting diesel to a fuel that is similar to gasoline, the work that has been accomplished in developing a SOFC APU operating on gasoline can be applied to the truck industry[1].

While the FPP is targeted for SOFC APUs, it is applicable to other fuel cell applications. For example, it can be used in hybrid fuel cell/conventional engine automobiles. In this application, the gasoline fuel will be refined to produce a lighter fuel that increases the life of the fuel cell reformer, while burning the heavier ends in the conventional engine. In addition, FPP can be used to refine distillate fuels as a back up fuel for the fuel cells being developed for the distributed generation market.

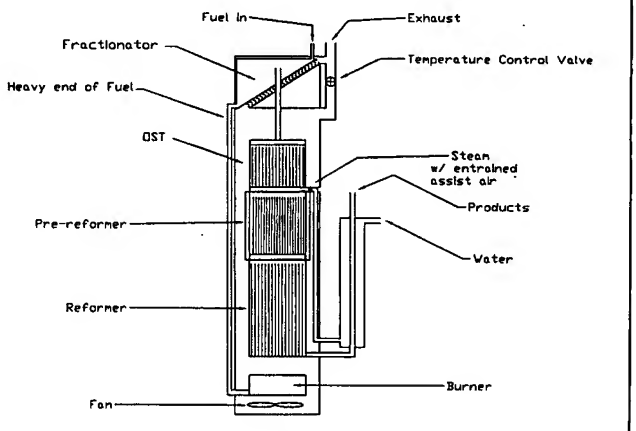


Figure 2- Logistic Fuel Preprocessor and Reformer (LFPPR) for a 20 Watts SOFC.

1.3 Status of the Technology

FPP is an extension of the fuel preprocessor technology that is part of the Altex Logistic Fuel Pre-Processor and Reformer (LFPPR). The LFPPR is being developed with the support of the Defense Advanced Research Projects Agency (DARPA). Under this Palm Power project, Altex and Pennsylvania State University (PSU), as a subcontractor to Altex, are developing a micro reformer for 20 W electric soldier and robot system applications. Figure 2 shows the LFPPR. An essential part of the LFPPR is the fuel fractionator, that is located at the top of the system. Logistic fuel (JP8 and diesel) enters the fractionator from the top. The light fuel fractions evaporate and separate from the heavy ends that flow down into the micro-burner located at the bottom of the unit. This micro-burner, that is based on the Altex proprietary Porous Surface Element (PSE) burner, consumes the heavy ends to produce the heat needed for the pre-reforming and reforming modules and the fractionator. The fractionated light ends enter an Organic Sulfur Trap (OST) that captures the remaining fuel sulfur and then flow into the steam prereformer and

[1] Delphi Automotive Publications, i.e. 2000 Fuel Cell Seminar Proceedings, page 530.

reformer, stacked compactly on top of one another. OST is based on a technology that has been developed at PSU. Also, PSU is supporting the catalyst developments for the reformer.

The LFPPR DARPA program is a three year program, that started in late 2001. So far, the testing and analysis work performed under this program has proven the feasibility of the fractionator. Under the DARPA program, diesel fuel is considered as a backup fuel to the primary JP-8 fuel. To compare a fractionated diesel to JP-8, a diesel fuel was fractionated to the FBP of JP8. Figure 3 shows the distillation curves of the parent diesel, the fractionated diesel and two JP-8 samples. As shown, JP-8 and the fractionated diesel distillation curves are identical, indicating that the fractionated diesel and the JP-8 are similar. More analysis of the fuel is under way to compare the chemical components of the fractionated fuel to the parent fuel and to JP-8. Nevertheless, tests to date demonstrate that the fractionated diesel is a better quality fuel than the parent diesel. As shown in Table 1, it has a higher hydrogen to carbon ratio and has less sulfur and nitrogen than its parent fuel. As shown, the fractionated diesel has 53% less sulfur, and 70% less nitrogen. These are considerable reductions, considering that only 40% of the fuel by volume, equivalent to 32% by weight, was removed as the heavy ends fraction.

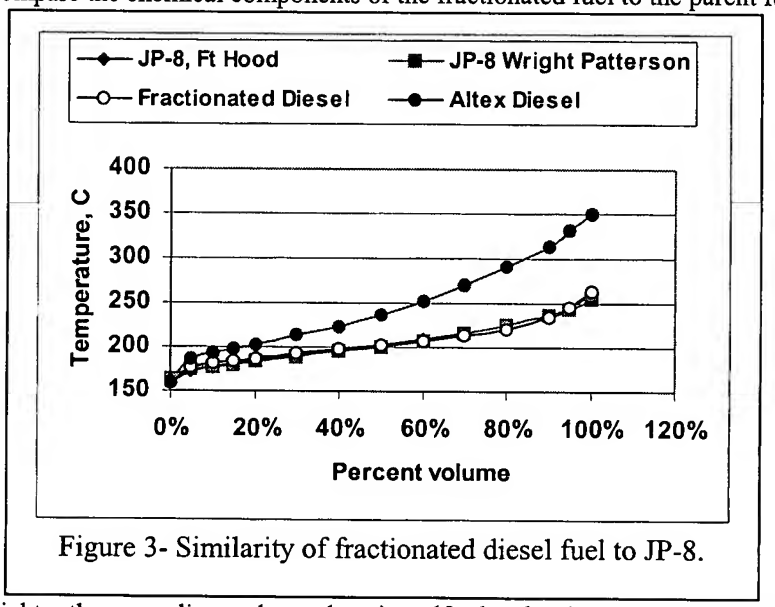


Figure 3- Similarity of fractionated diesel fuel to JP-8.

For an efficient LFPPR, the heavy end fraction is limited to 32%. This is defined by the amount of the heat required for the reforming step. In the APU system, the heavy ends are returned to the tank, and therefore, there is no practical limit on the fraction of the heavy ends that can be removed by the fractionator. It is expected that the fractionator can remove enough heavy ends to make the fuel as light as, or lighter than, gasoline and to reduce its sulfur level to less than 30 ppm that is required for SOFC fuel cells.

Table 1- Fuel Analysis Results

Fuel sample	Sulfur, ppm	Nitrogen, ppm	Carbon, %	Hydrogen, %	H/C ratio
JP-8 Wright Patterson	736	3.8	85.16	13.51	0.1586
JP-8 Ft Hood Texas	189	24.9	85.17	13.45	0.1579
Diesel Fuel	163	119.9	86.54	13.73	0.1587
Fractionated Diesel	77	36.2	85.66	13.73	0.1603

1.4 Why DOE funds are needed

DOE funds are needed to develop a prototype FPP for a 5 Kwe SOFC APU system. This unit uses a fractionator that handles 250 times more fuel than the fractionator that is used in the DARPA LFPPR. In addition, the FPP requires heat recovery systems that are shown in Figure 1. These heat recovery modules are particular to the proposed FPP and are required for efficient and safe operation of the system. The DOE program will also address the integration of the FPP with a truck and with a SOFC APU. The program will also define the optimum design parameters, such as the fractionation temperature, the light and heavy end fractions and the output sulfur. While a separate effort is needed to develop the FPP for the APU/SOFC system, the larger DARPA supported LFPPR effort will offer substantial synergies supporting the FPP effort. For example, the fundamental data that are being generated for the design of the fractionator in the LFPPR will be useful in designing the FPP fractionator. In addition the facility, equipments and diagnostics used under the LFPPR DARPA project will be used in developing the FPP.

2. Project Description

2.1 Introduction and proposed approach

The purpose of this project is to develop and test a prototype Fuel Preprocessor (FPP) that will convert the diesel fuel to a clean fuel suitable for use with SOFC APU systems. Currently trucks have to operate at idle for approximately eight hours a day to keep the engine warm and/or to produce the needed heat or air conditioning for the driver's comfort at rest stops. This results in $80x10^{12}$ Btu/year energy loss, produces 60,000 TPY NOx, 9.6 million TPY CO_2 and costs the truck industry nearly one billion dollars per year in fuel costs alone. Realizing these enormous energy, environmentl and economic penalties, DOE has targeted the US truck fleet APU as a prime target to be converted to a SOFC fuel cell. However, the development of a

SOFC APU has been held back by the difficulty of reforming diesel fuel. Diesel fuel contains heavy ends that result in carbon deposition and make it a challenging fuel to reform. It also can have up to 500 ppm sulfur, while SOFCs are limited to 30 ppm sulfur. Because of these difficulties, Delphi, the front runner SOFC APU developer under the DOE SECA program, has been limiting their tests to sulfur free gasoline. While substantial progress has been made, these developments are not directly transferable to the truck industry, that uses diesel fuel. The Fuel Preprocessor(FPP), proposed under this program, makes these developments relevant to the truck industry. This is achieved , by refining the fuel on board to make a gasoline like fuel out of the diesel fuel. FPP is also projected to remove the majority of the sulfur, so that the clean fuel can be used directly in the SOFC/APU.

The project approach is to use a fractionator to remove the heavy ends. As shown in Figure 1, the fuel is pumped from the truck fuel tank to the fractionator. The fractionator boils the light fractions that are transported to the SOFC reformer. The heavy end fuel fraction is discharged from the fractionator back to the fuel tank after passing through the heat recovery and air cooler components. The heat required for the fractionation is provided by the Altex proven PSE burner. Alternatively the waste heat from the SOFC can be used for the fractionation. The FPP is projected to be one cubic feet in volume and weigh 1.5 pounds and produces 0.6 gal/hr clean fuel.

It should be noted that, due to funds limitation, no additional sulfur removal step is envisioned under this project However, this step can be added later, if the FPP does not reduce the sulfur level to below 30 ppm. As discussed above, PSU is developing the OST technology for LFPPR. This technology can be incorporated into the FPP in the future, as needed. Results discussed above, showed that by removing 40% of the fuel volume, 53% of the fuel sulfur was removed. It is envisioned that by fractionating and removing 80% of the fuel, a substantial fraction of the fuel sulfur is removed. Tests planned under this project will define this level.

2.2 Technical feasibility

The feasibility of the fractionator is already proven. In addition to being a proven technology in large scale in the refining industry, Altex work under the DARPA supported LFPPR program has shown the feasibility of implementing fractionation in small units. The Altex PSE Burner has also been proven to operate on diesel fuel for extended periods. The FPP heat recovery components, and Balance of Plant (BOP) equipment are also feasible, based on LFPPR experience.

2.3 Technical hurdles to be overcome by proposed project

While FPP is technically feasible, work is required to develop an effective, efficient, compact and safe FPP prototype. The fractionator needs to be developed to effectively separate the light fractions from the heavy ends with minimal co-boiling. To minimize co-boiling, the fractionator may require multiple boiling and condensation stages. This requirement needs to be balanced with the system weight and volume. Also the fractionator external surface area, and the needed heat transfer augmentation fins have to be determined. For an efficient system, effective heat recovery is needed. While, heat exchanges are available, the challenge is to recover the heat using compact heat exchangers. Finally, the system consists of integration of several components that need to work in concert and also be integrated with a truck and an SOFC APU system. All these issues will be addressed under the proposed program.

3. Benefits

There are over 480,000 heavy duty trucks on US roads. A substantial amount of energy is lost, when trucks idle to keep the engine warm, or to produce electricity, heat or air conditioning for the sleeper compartment. While idling, the truck also produces substantial amount of emissions. By replacing the idling practice with a FPP SOFC/APU, considerable energy, economic and environmental benefits are gained. Although SOFC based APUs potentially have several advantages, their success strictly depends on the complex diesel fuel reforming process. It is in this area, that the proposed innovative FPP-SOFC APU will add significant value to the SOFC APUs under development.

Table 2 summarizes the projected energy, economic and environmental benefits for the proposed technology. Based on Pacific Northwest National Laboratory (PNL) studies, on average a Class 8 truck consumes 1700 gallons of diesel fuel per year[2] just idling. At a diesel price of $1.2 per gallon, the fuel cost during idling is $2040 (shown as base technology in Table 2). This translates into 219.3 MM Btu/yr of energy consumption. Trucks fitted with the FPP-SOFC-APU Technology will consume only 428 gallons/year of diesel. This value was calculated by using 420 gallons/year for a SOFC combination[2] and an additional 8 gallons/year for the heat needed for the FFP to function. This difference in diesel usage will result in savings of about $146.5 million for the entire sample fleet per year, assuming only 20% of the Class 7&8 trucks in US are fitted with the proposed technology. Apart from diesel usage, each truck spends about $2300 on maintenance and overhaul due to engine wear because of idling[3]. This results in cost savings of about $220 million for the entire sample fleet with the proposed technology. Therefore a total savings of approximately $366.5 million can be realized using the SOFC technology for APUs. The last column in the Table 2 is an estimate of savings due to the FPP addition to the SOFC technology. This is half of the

[2] Don McConnel, Transportation Applications for SOFC-Auxiliary Power, US DOE, PNL, June 2000.

[3] http://www.anl.gov/OPA

total savings, and was calculated by assigning a 50% probability of success for the development of a diesel fuel SOFC/APU system without the FPP system add on.

Table 2 also shows the energy savings. As shown, by implementing a FPP SOFC/APU to 20% of the truck fleet, 7,800 billion Btu energy is saved each year.

Table 2: Energy, Economic and Environmental Benefits of the Proposed Technology.

Parameters	Base Technology /Unit	FPP-SOFC-APU Technology/Unit	Savings/Unit	Savings with 20% market penetration	**Savings due to FPP Add on**
Diesel fuel (gal/year) use	1700	428	1280	122.9 MM	61.45 MM
Energy spent/year	219.3 MM Btu	55.2 MM Btu	164.1 MM Btu	15,754 Billion Btu	**7,800 Billion Btu**
Diesel cost/year	$2,040	$514	$1,526	$146.5 MM	$73.25 MM
Idling (per year) maintenance cost	$2,300	$10	$2,290	$220 MM	$110 MM
Total Cost/year	$4,340	$524	$3,816	$366.5 MM	**$183.3 MM**
CO2 emission	20 TPY	1.5 TPY	18.5 TPY	1.78 MM TPY	**0.89 MM TPY**
Nox emission	250 lbs/year	Negligible	Negligible	12000 TPY	**6000 TPY**
CO emission	420 lbs/year	Negligible	Negligible	20160 TPY	**10080 TPY**

Prior studies show that a single truck contributes up to 20 tons of CO_2, 420 lb of CO and 250 lb of nitrous oxides, while idling[4]. The NOx and CO emissions from the proposed FPP-SOFC-APU technology will be virtually insignificant and CO_2 emissions will also be very low compared to idling. As shown in Table 2, by implementing the proposed technology to 20% of the truck fleet, 6000 TPY of NOx emissions, 10180 TPY of CO and 0.89 Million TPY of CO_2 emissions are prevented from polluting the atmosphere. These are substantial benefits.

4. Project Plan

The objective of the proposed program is to develop and test a prototype Fuel Preprocessor (FPP) that efficiently and safely converts the diesel fuel into a clean fuel suitable for a SOFC APU system.

4.1 Task 1-FPP Design Refinement

The purpose of this task is to refine the FPP system design. This task consists of three subtasks. The purpose of Subtask 1.1, is to design the FPP process by performing process calculations. The purpose of Subtask 1.2 is to design the FPP's components. Finally, the purpose of Subtask 1.3 is to produce the integrated FPP design.

Subtask 1.1-At the initiation of this task, the FPP system specifications will be defined. In particular, the target fractionator temperature and the level of fractionation will be defined in this task. For this purpose, the SOFC APU developers will be contacted to collect information on the latest status of the SOFC/APU developments. In particular inputs from Delphi Automotive, a major developer of the SOFC APU under the DOE SECA program will be used to define the needed fractionation level for their system. In their recent developments, Delphi has been testing their SOFC/APU unit with gasoline, because of the diesel fuel reforming challenges discussed above. This suggests that the diesel fuel needs to be fractionated to remove all the heavy ends beyond the gasoline FBP of 200C. As per Figure 3 data, approximately 80% of the fuel volume (64% weight) needs to be fractionated and removed. This is possible and is desirable, since it may reduce the sulfur level of the majority of diesel fuels to below the 30ppm, the SOFC tolerance limit.

After defining the fractionator temperature, process calculations will be performed for a 5 Kwe FPP/SOFC system. For this calculations, WinSim, an available commercial chemical process module, and Altex Thermo Fluid Model (ATFM) will be used to define the system flows, energy, heat loss, temperatures and pressure drops. These modules are available and are currently being used for the LFPPR design.

Subtask 1.2-Following the process design, the FPP components will be designed. The components include, the fractionator, micro-burner, heat exchanges, air cooler and balance of the plant (pumps, fans, vales and controls). The design procedure will follow procedures, and will utilize tools that are being applied in the LFPPR project. The test data generated under the LFPPR program will also be used to define the fractionator internal surface area. A sample of Altex fractionator evaporation rate versus heat input is shown in Figure 4. The heat transfer calculations and data will be used to define the

[4] Wendy Leavitt, Fleet Owner magazine, "http://www.truckinverter.com"

fractionator external surface area for proper heat transfer. Based on the LFPPR design and test experience, the fractionator requires fins on the hot gas side for proper heat transfer.

The micro-burner will be designed based on the Altex Porous Surface Element Burner (PSEB). This burner has been demonstrated for the US army at 2000 Btu/hr (600 W) as a Trioxane bar replacement, operating on diesel fuel and using natural convection. The burner is currently being tested with diesel fuel and forced air with a HiZ thermoelectric module that provides 2We power. A picture of the disassembled unit is shown in Figure 5. The burner is shown in the front. It is a 5 cm by 5 cm by 0.5 cm burner, producing 1400 Btu/hr (400 W). Referring to Figure 5, the burner box is shown behind the burner. The Burner box contains the burner, ceramic insulation and the fan. This unit will slide under the thermoelectric unit shown on the left, to produce electricity for military battery chargers. The burner is scalable, and has been scaled down to 50 W. The same burner technology is being used in LFPPR.

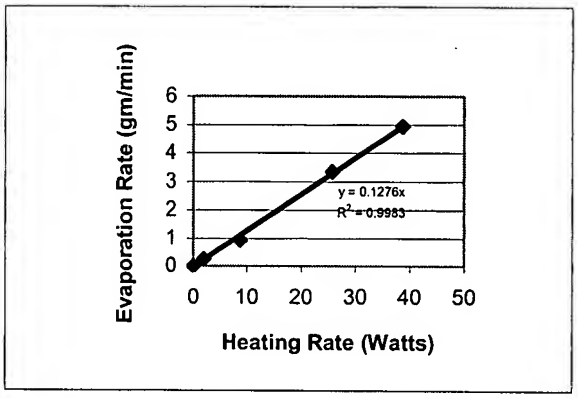


Figure 4-Fractionator evaporation rate.

To avoid pluggage with diesel and heavy ends, the burner uses the Altex Porous Surface Element (PSE) that pumps and vaporizes the fuel. The PSE is designed with graded passage sizes and recessed cooler areas so that heavy ends and deposits do not plug fuel paths. The burner has been tested for extended hours under continuous and cyclical operation on diesel and jet fuels. Based on preliminary calculations, the FPP burner needs to produce 500 Btu//hr (150 W). The burner capacity and the PSEB design experience discussed above will be used to define the burner size for the FPP unit.

The heat exchangers and the cooling system will also be designed under this task. Again available models and data that are being generated under the LFPPR program will be used.

Subtask 1.3- The component designs will be integrated together to create the system integrated design. In the integrated system, fuel pumps, air fan, controls will be defined. The issues with system startup will also be defined under this subtask.

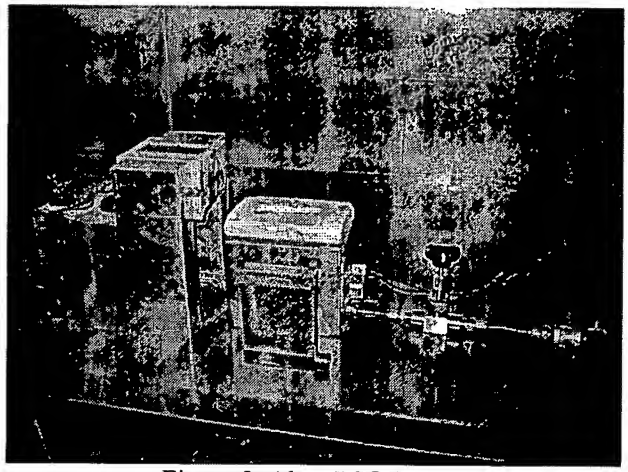


Figure 5- Altex PSE Burner

4.2 Task 2-FPP Prototype Design, Fabrication and Tests

The purpose of this task is to design and fabricate a prototype FPP for laboratory testing and evaluation. This task consists of four subtasks. The purpose of Subtask 2.1 is to translate the Task 1 FPP system design to a prototype FPP for laboratory testing. The Purpose of Subtask 2.2 and 2.3 is to, respectively fabricate and test each FPP component. Finally, the purpose of Subtask 2.4 is to combine all the individual components and test the integrated FPP prototype.

Subtask 2.1-Since the scale of the prototype system is the same as the full-scale system that is designed in Task 1, the same design will be used for the prototype system. However, the needed flexibility and instrumentation for testing will be included in the prototype.

Subtasks 2.2 and 2.3- Initially, each component will be fabricated and tested, to resolve performance issues concerning each element. As the test data become available, they will be analyzed (under Task 3 activities) and the results will be used to improve and optimize each component, as needed.

Initially, the fractionator component will be emphasized, to define early on in the program the challenges and issues with this unit. As needed, pre-prototype units will be rapidly fabricated and tested to progressively evolve the final prototype fractionator. This approach has been found effective in the LFPPR development. As an example, Figure 6 shows a pre-prototype micro fractionator made out of glass. In addition to being a cost effective and fast approach of fabricating a pre-prototype, the use of glass allows visualizing the path of the liquid in the micro-fractionator. This issue is important in the LFPPR system, which handles only 0.1 ml/min of the fuel and is desired to use the liquid surface tension to make the system relatively insensitive to orientation. As shown in Figure 6,

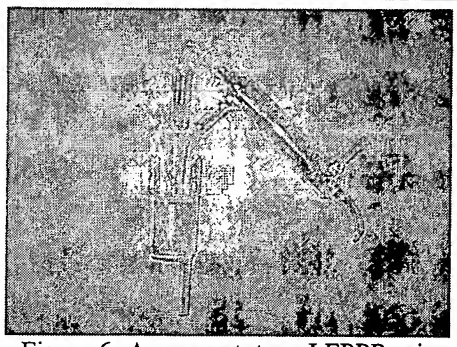


Figure 6- A pre-prototype LFPPR micro fractionator and condenser (diameter 1cm).

the fractionator is equipped with a micro condenser, to collect the clean fuel for later analysis. A condenser is not part of the FPP system. However a similar test approach will be used in the project to collect samples of the clean fuel to asses its quality. It should be noted that the FPP fractionator is projected to handle 80 ml/min (approximately 1.2 gal/hr) for 80% heavy ends fraction and is projected to operate on a truck, when it is parked at the rest stops. Therefore, it can have a free liquid level. These issues make the FPP development less challenging than the LFPPR fractionator.

The quality of the fractionated light ends will be assessed by analyzing the condensed clean fuel. Outside analytical laboratories will be used for this purpose. Tests will include, distillation curves, sulfur analysis and analysis of aromatics. This data will be compared to gasoline sample test results, to define the effectiveness of the fractionator in refining diesel fuel to a gasoline-like fuel. As a cost share item, Altex is upgrading its facilities to include a Gas Chromatograph (GC). The GC will allow evaluating the quality of the fractionated fuel on line.

The prototype burner development will make use of Altex's prior experience. The burner will consist of a stamped thin metal reservoir that holds the PSE wick. Vaporized fuel is then mixed with the air that is entrained through the perforated screens. The PSE AMETEK ceramic woven fiber wick is designed to draw the fuel from the reservoir and evaporate the fuel without plugging the wick. Using the available heat output versus wick length and heat output versus screen area correlations, the wick length and screen area can be determined. The burner is projected to be 3 cm by 3 cm and 0.5 cm in thickness. The prototype burner will be fabricated out of stainless steel.

To start up the burner, a small electric wire resistance heater will be embedded into a short section of the center edge of the wick. During startup, battery power will be used to vaporize a small quantity of fuel from the wick. A standard piezoelectric spark type igniter will be placed in close proximity to a portion of the heated wick to ignite the vapor. Once a flame is initiated, it will heat the wick and promote ignition of the entire wick. This ignition approach has been demonstrated in Altex bench experiments.

Tests will be planned to demonstrate how the fractionator and the PSE burner operate together. Anticipated tests, to be included in a test plan, are listed in Table 3.

Table 3 - Fractionator and Burner Element and Integrated System Tests

Fractionator Temperature Ranges The fractionator temperature range will be varied to define its effectiveness in fractionating the fuel.
Heat Output and Heat Transfer The fuel flow rate will be measured and compared to the measured heat generation rate, calculated from the load and the exhaust conditions.
Emissions Emissions and O_2 will be measured to define flame quality. Emissions will be compared to the performance goals.
Cold and Hot Temperature Operation The burner will be subjected to temperatures down to –18C (0F) in a cold chamber and up to 52C (125F) in a hot chamber and then tested.
Fuel Flexibility Burner performance will be tested on diesel and fractionated heavy ends
Consistency of Heat Output Over Time The burner will be tested for its longevity

Initial tests will focus on proper operation of the micro-burner. For the specified heat load, the burner will be brought to steady operation and measurements of emissions, temperatures and flow rates recorded.

As listed in Table 3, once burner/fractionator operation has been found acceptable under standard conditions, several tests will be performed to assess operation under different environments. An available cold chamber will be used to test the burner down to -18C and up to 52C.

After the basic performance tests are completed, the burner/fractionator will be operated for over 500 hours and inspected on a periodic basis to note degradation or clogging, and any other component degradation. Output capacity drop off with time and emissions or temperature excursions will be used as a measure of degradation. Also, the system will be disassembled and visually inspected to note any degradation.

The heat recovery components will also be tested under this task. It is anticipated that off the shelf heat exchangers will be used. Altex has considerable experience in heat recovery, and has used off the shelf and custom made heat exchangers in its previous developments. As an example, the system shown in Figure 5, uses four heat exchangers on the hot and cold side thermoelectric module. When off the shelf systems are not available, Altex works closely with heat exchanger manufacturers, to cost effectively fabricate the needed components. For example Altex has used Stall Inc, a custom heat exchanger manufacturer, to fabricate a high temperature heat exchanger heating a gas turbine working fluid operating with biomass fuel. Altex also has considerable experience with fuel pumps and cooling fans.

Subtask 2.4-The integrated prototype system will combine all the elements developed and tested under this task to produce the FPP integrated prototype. The system will be insulated to minimize heat loss. In recent developments, Altex has made use of different materials and their properties to make an effective insulation package. For example, in the Figure 5 set

up, both ceramic and Aerogel materials are used. Ceramic insulation is machined and formed to produce the needed air channels around the burner. Aerogel is used behind the ceramic to increase the insulation effectiveness. A similar approach is expected to be used for the FPP prototype. After integration of the heat recovery components, BOP and insulation, the integrated FPP will be tested as per Table 3 test plan. These will define the FPP efficiency, and its effectiveness to refine diesel to a gasoline like fuel.

4.3 Task 3-Performance and cost evaluation

The purpose of this task is to evaluate FPP and compare its performance parameters with the goals set at the beginning of the program. This task consists of two subtasks. The purpose of Subtask 3.1 is to define the FPP performance and the purpose of Subtask 3.2 is to define its cost, and its economic, energy and environmental benefits.

Subtask 3.1- Under this subtask, the Task 2 test data will be reduced and analyzed to define the FPP effectiveness in removing heavy ends and sulfur from diesel. The quality of the FPP clean fuel will be compared to the gasoline specs to define the effectiveness of the FPP. This evaluation will be performed concurrent to the testing performed under Task 2. The results of this task will be used to optimize the FPP components as needed. The system efficiency, safety flexibility and durability will also be evaluated. Prototype data will also be used to define the system weight and volume.

Subtask 3.2- Under this subtask, the cost of the FPP will be defined. Fabricator and manufacturer inputs will be collected to define the FPP system cost. The cost of the system will be used to define the impact of the FPP on the SOFC APU system cost. This information will be used to define the economic impact of the FPP/SOFC APU system on the truck industry. The system energy and environmental benefits will also be defined. This information will generate the needed input for preparing the FPP Business Plan, that will be prepared by Altex after the successful conclusion of this project.

4.4 Task 4-Project management and reporting

The purpose of this task is to apply the necessary resources to manage project tasks and milestones and provide corrective action when needed. In addition, semiannual reports and a final report will be produced under this task. Semiannual reports will cover project status and plans, and highlight any problems and correction strategies. The final report will document the progress made under this project and document the FPP preliminary commercialization plan.

4.5 Project Schedule and Milestones and cost breakdown

Table 4 and 5 show the project statement of work and Schedule, respectively. The dates are based on an assumed start date of 4/1/2002.

Table 4- Statement of Work

Task #	Task Title	Completion Date	Responsible	Projected Federal Cost	Projected None Federal Costs
Milestone 1 (Task 1)	Complete design	12/31/02			
Subtask 1.1	Process Design	8/30/02	Altex, Eng.	36,000	
Subtask 1.2	Components Design	10/30/02	Altex, Eng.		
Subtask 1.3	Integrated System Design	12/31/02	Altex, PE[5]		
Milestone 2 (Task 2)	Prototype Testing	12/31/03	Altex, Eng.	119,000	20,000
Subtask 2.1	Prototype Design	1/31/03	Altex, Eng		
Subtask 2.2	Components Fab.	5/30/03	Altex, Tech		
Subtask 2.3	Components Tests	8/30/03	Altex, Eng.		
Sub task 2.4	Integrated tests	12/31/03	Altex, PE		
Milestone 3 (Task 3)	Evaluate system	5/30/04		31,000	
Subtask 3.1	Performance Evaluation.	1/31/04	Altex, PE		
Subtask 3.2	Economic Evaluation	5/30/04	Altex, PE		
Milestone 4 (Task 4)	Management and Reporting	6/30/04		14,000	
Subtask 4.1	Semiannual report	1/2/03, 7/1/03 and 1/1/04	Altex, PI		
Subtask 4.2	Final Report	3/31/04	Altex, PI		
Total				200,000	20,000

[5] PE=Project Engineer

Table 5- Project Schedule

Task #	Task Title	3QT02	4QT02	1QT03	2QT03	3QT03	4QT03	1QT04	2QT04
Milestone 1 (Task 1)	Complete design		X						
Subtask 1.1	Process Design	X							
Subtask 1.2	Components Design		X						
Subtask 1.3	Integrated System Design		X						
Milestone 2 (Task 2)	Prototype Testing						X		
Subtask 2.1	Prototype Design			X					
Subtask 2.2	Components Fab.				X				
Subtask 2.3	Components Tests					X			
Sub task 2.4	Integrated tests						X		
Milestone 3 (Task 3)	Evaluate system								X
Subtask 3.1	Performance Evaluation							X	
Subtask 3.2	Economic Evaluation								X
Milestone 4 (Task 4)	Manag./ Reporting								X
Subtask 4.1	Semiannual report		X		X		X		
Subtask 4.2	Final Report								X

4.6 Commercialization Strategy

Altex is an energy and environment research, development and deployment company. Altex has supported manufacturers, as well as other private and government clients, in fuels, combustion and emissions control developments. Clients include the Gas Research Institute (GRI), Southern California Gas (SCG), U.S. EPA, U.S. DOE, DOD, EPRI, Eclipse Combustion, Gordon Piatt Energy Group, Cleaver Brooks, NIECO, Alzeta, Riley Stoker, Weyerhaeuser and Svedala. To commercialize technologies, Altex works cooperatively with manufacturers. For example, Altex has developed and tested a low-NOx burner for boilers, which is currently being built and tested at full scale at major burner manufacturer test facilities in preparation for field testing and commercialization. As another example, Altex developed and tested a high efficiency burner for NIECO's meat broilers. This burner is being manufactured and is installed in hamburger broilers used in the Burger King and Carl's Juniors fast food chains.

Consistent with this approach, Altex will license the FPP to a SOFC/APU manufacturer, such as Delphi, who will commercialize the FPP with their SOFC/APU system. Since the FPP will expand the manufacturers market from gasoline fueled vehicles to diesel trucks, they will be willing to invest and commercialize the unit. While the FPP is targeted for SOFC APUs, it is applicable to other fuel cell applications. For example, it can be used in hybrid fuel cell/conventional engine automobiles. In this application, the gasoline fuel will be refined to produce a lighter fuel that increases the life of the fuel cell reformer, while burning the heavier ends in the conventional engine. In addition, FPP can be used to refine distillate fuels as a back up fuel for the fuel cells being developed for the distributed generation market. Recent California energy crises experience has demonstrated that relying on one fuel for power generation is highly risky.

The FPP also has military applications. It can be used to refine the logistic fuels and produce a lighter fuel for military fuel cell applications. The heavy ends can then be consumed in the military vehicle or, military kitchens and naval vessels.

In summary, the FPP will have many applications and appeal in the fuel cell industry. It will make fuel cells more fuel flexible, and as result, when developed it will generate considerable interest from different sectors of the fuel cell industry who will be willing to license, invest and commercialize the technology.

5.0 Project Management Plan

5.1 Project Organization and Responsibilities

Dr. Namazian will be the Project Manager and Project Engineer (PE) on the proposed effort, as well as Task Manager for Tasks 1, 3 and 4. He will be responsible for the overall budgetary and technical success of the project, as well as the FPP design, evaluation and reporting. Dr. Kelly will assist Dr. Namazian during the design and evaluation in Task 1 and 3. Task 2 will be managed by Siva Sethuraman who will be responsible for fabrication of test articles, test setup and testing.

5.2 Task Integration and Project Coordination

Dr. Namazian, who identified the FPP concept, will coordinate the Altex efforts as Project Manager. FPP design activities, managed by Dr. Namazian in Task 1, will feed directly into and support test system design, and fabrication activities in Task 2. He will be responsible for obtaining needed design inputs from Delphi, a SOFC APU developer that will feed into Task 1. Task 2 activities, to build and tests the prototype system, managed by Siva Sethuraman, will feed into Task 3 –Performance and Cost Evaluation. Dr. Namazian, who has fuel cell system analysis and economic analysis background will integrate both performance and cost results to quantify the benefits of the FPP. The results of the program will be documented in needed reports.

5.3 Project Management Structure

To manage the project, weekly expenditures will be tracked by Dr. Namaazian and progress towards milestones will be assessed. Using these two pieces of information, both budget and schedule variances will be defined. If variances exceed 15%, corrective action will be taken to reduce variances.

6. Technical Capabilities

6.1 Key Personnel

Dr. Mehdi Namazian will lead this program. He is the principal investigator on the DARPA $2.4 million LFPPR development program. The FPP development is closely linked to the LFPPR development and by having the same PI, the parallel developments will be well coordinated. Dr. Namazian has over 20 years of experience in fuels and combustion research, including 10 years of collaborative turbulent gas flame research at Sandia National Laboratories, Combustion Research Facility. During this effort, he led a multi task, multi participant collaborative program with MIT, Caltech, Gaz De France and Sandia National Laboratories. Under this program, high power laser diagnostics, and sophisticated modeling tools were used to characterize a prototype burner, and extend results to full scale. In addition to over 25 scientific publications, and unique models and data bases, this program led to the development of two low NOx burners at Altex. This unique experience will be used on this program. Besides this fundamental combustion experience, Dr. Namazian has performed applied research on gas burners for boilers and gas turbines and diesel engines. At Altex, as the technical leader on the development of a PSE burner for the army, he has considerable experience with liquid logistic fuel handling and utilization. This experience is directly relevant to the FPP program. He has a Ph.D. in engineering and has written over 50 articles on combustion. He is a holder of three U.S. patents. His resume is attached to the end of this proposal.

Dr. Namazian will be assisted by Dr. John Kelly and Siva Sethuraman. Dr. Kelly has 28 years of experience in fuels and combustion research and development and has managed over $20 million in research and development efforts over that the span. Siva Sethuraman has a MS in chemical engineering from Penn State and has worked for Process Combustion Corporation developing combustion based thermal oxidizers for various industries.

6.2 Related Experience

The fractionator development under the LFPPR program is directly relevant to this project. As the inventor of this technology, Altex is leading fractionator development under the DARPA effort and will be responsible for the integrated LFPPR/Fuel Cell system design, fabrication and testing. All these efforts are directly relevant to the FPP proposed project. Altex has also been developing and testing a Low Cost Pocket Stove (LCPS) for the Army (Natick). This stove utilized a 600w burner that reliably burns diesel, JP8, and kerosene. A critical need of this development was to be able to operate the burner long term on diesel fuel without pluggage or fall off in output and with no luminosity. Altex addressed these dual challenges by developing the Porous Surface Element (PSE) special wick and perforated metal screen burner. The novel approach has been tested long term using an automated combustion test cycle apparatus at Altex. For solider use, the burner operates with the natural convection. Recently this burner has been converted to operate on forced air for heating a thermoelectric generator developed by HiZ corporation. A picture of this unit is shown in Figure 5.

6.3 Facilities and available equipment

Altex has over 4500 square ft of facility space, covering offices, fabrication shops and test facilities. Of this, 2000 square ft of space is dedicated to various combustion and fuel test facilities. This facility has a well equipped laboratory that is dedicated to the LFPPR fuel reformer development and testing. This facility is equipped with standard temperature and flow monitoring instrumentation. The facility is also equipped with standard emission monitors. As a cost share item, Altex will upgrade this facility to include a Gas Chromatograph. With this additional analytical tool, all the necessary diagnostics are available to successfully execute the project. A data acquisition system is available which collects and stores the data. This facility also has all the necessary equipment for fuels testing and fuels distillation. This equipment is being used for the development of the fractionator portion of the LFPPR under the DARPA program.

Task 3 – Fractionator Performance (Bench Scale)

JP-8 bench-scale fractionator performance is excellent

Reference System

	Parent Fuel	Fractionated Fuel (Residue)	Percent Reduction
Sulfur, ppm	736	371 (1783)	50%
Poly Aromatic, %	2.55	1.4	45%
Carbon Residue,%	0.008	<0.001	

Bench-Scale Fractionator

	Parent Fuel	Fractionated Fuel (Residue)	Percent Reduction
Sulfur, ppm	736	473 (1234)	36%
Poly Aromatic, %	2.55	1.71	33%
Carbon Residue, %	0.008	<0.001	

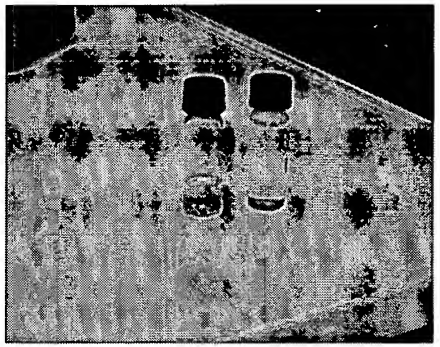
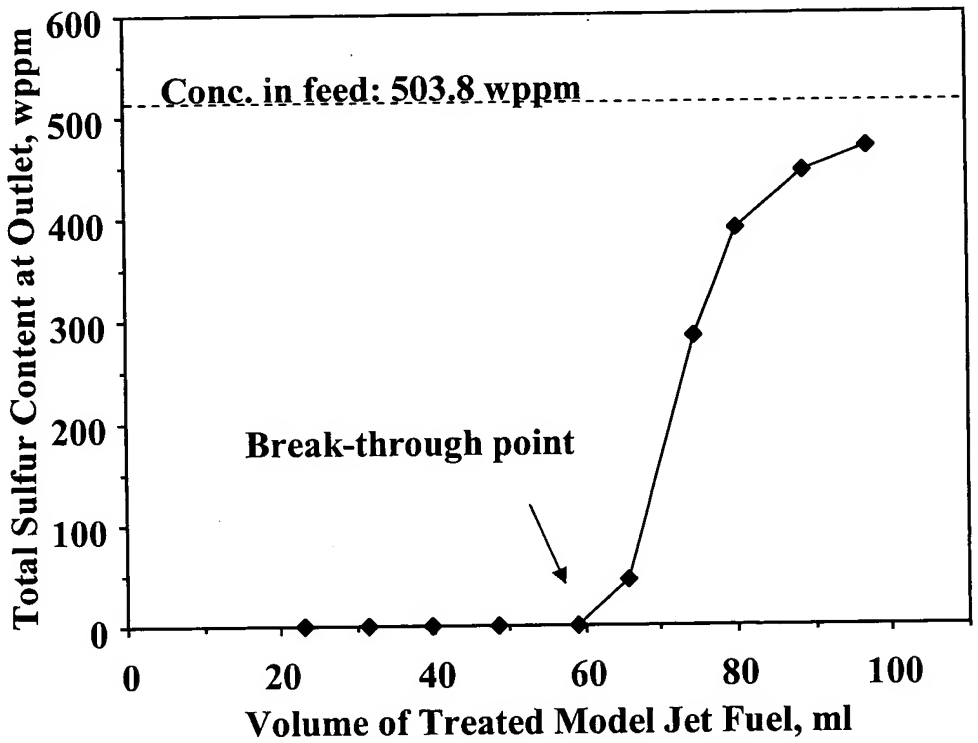


Exhibit 7

Adsorption Profile of MJF over A-2 at Ambient Temperature

•Since March, the adsorbent capacity has been improved by a factor of two

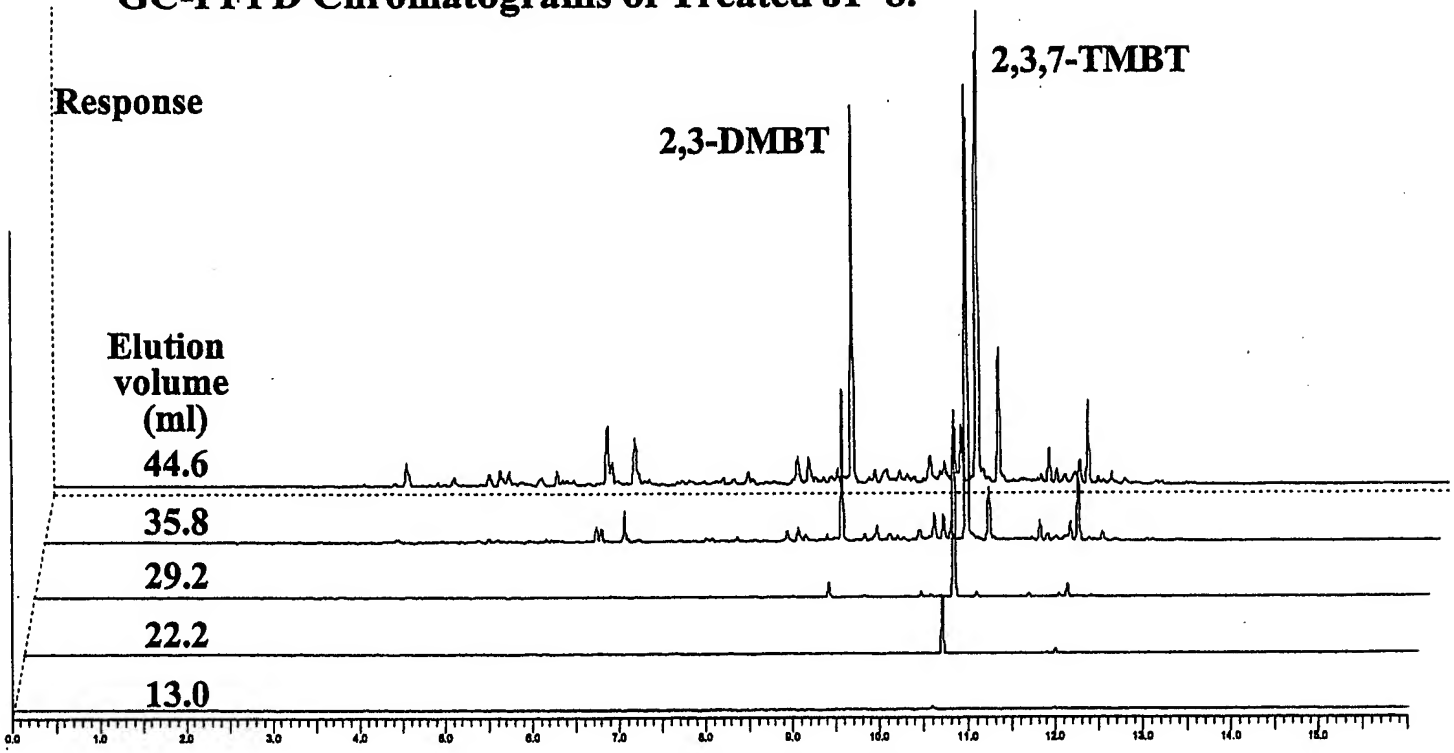


- **Conditions:**
  - **Feed: MJF**
  - **Adsorbent: A-2**
  - **Temperature: ~25°C**
  - **Adsorbent bed: 1.25 ml**
  - **Adsorber type: flow up**
  - **Stainless column: 4.6 mm i.d.**
  - **LHSV: ~ 24h^{-1}**
- **Break-though Capacity:**
  - **18.3 mg-S/ml-A-2(bulk)**
  - **(~10.9 mg-S/g-A-2)**

Exhibit 8

Fuel Desulfurization Results

GC-PFPD Chromatograms of Treated JP-8.



Conditions:

Adsorbent: A-2,
80-100 m^2/g, designed especially for on-board or on-site fuel desulfurization for fuel cell applications

JP-8, S=736 ppm
Ambient temperature and pressure
Glass column, 11 mm i.d.
Adsorbent amount: 3.2 ml

Ex hibit 9

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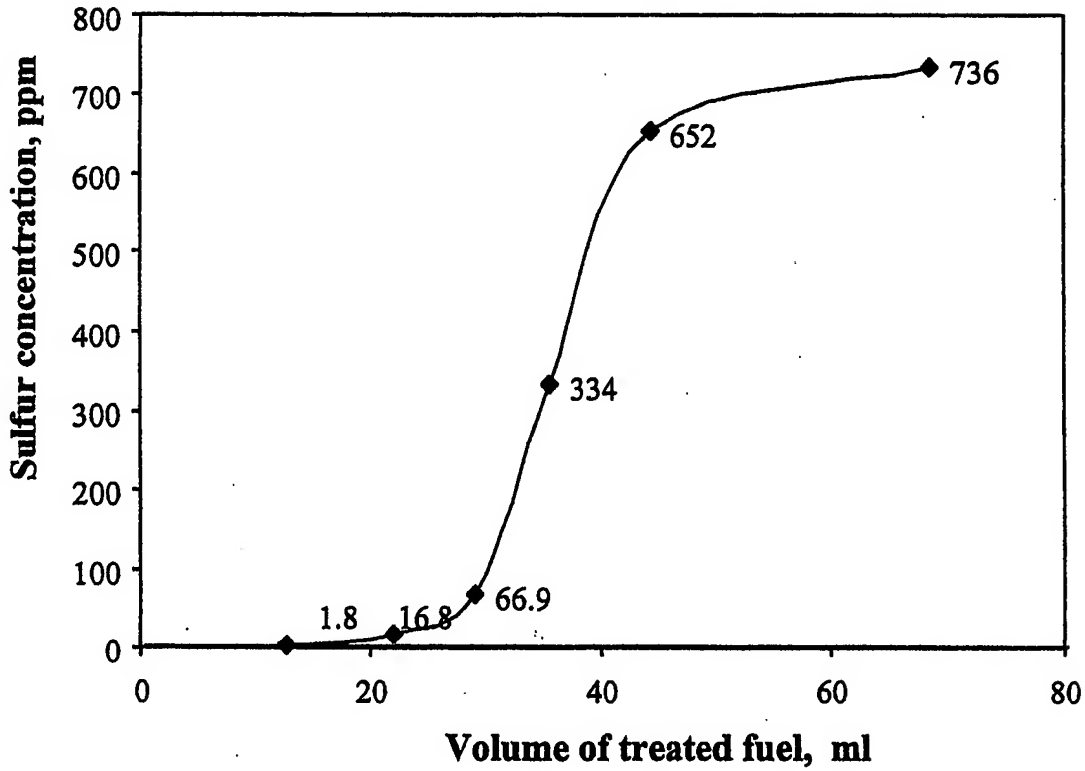
Fuel Desulfurization Results



Conditions: **Feed: JP-8 (S=736 ppm)**
Ambient temperature and pressure
Adsorbent: A-2
Glass column, 11 mm i.d.
Adsorption bed volume: 3.2 ml

Exhibit 10

ALTEX TECHNOLOGIES CORPORATION

PENNSTATE

analyzing the mixtures were obtained after changing various carrier gases, flow rate, operating pressure, and temperature program. The ideal conditions are as follows: inlet pressure: 25Psi; valve timing of 0.05 minutes on, followed by 5.4 minutes off; initial temperature: 40°C, hold 5min, then heat up to 210°C with a ramp of 10°C, and keep at this temperature for 10 min before cooling down to initial temperature.

Results and Discussion

Figure 21 shows the preliminary results for the steam reforming of a model jet fuel over a nickel catalyst (Sud-Chemie commercial G-91 with a composition of NiO/Al2O3.K2O.CaO). A maximum of 8.0 gram of catalyst was put into the reactor, which would be the maximum according to total Palm Power weight budget for the pre-reforming and reforming, and a necessary fuel flow rate of 5.6 ml/hr (4.2 g/hr) was initially used for catalytic test to meet 20 W Palm Power demand. Under the conditions of 800°C and the ratio of steam/carbon of 3:1, the preliminary catalytic results for pre-reforming/reforming are summarized in Figure 21.

From Figure 21 it can be seen that during a 5-hour run, a nearly complete conversion of model jet fuel is achieved. In the products, hydrogen is near 60 %, the contents of CO and CO_2 are close to each other (around 15~19% each). At the initial stage, the formation of methane is around 10%, then it stabilizes at 2.0%. A small portion of ethane and C3 were also observed at the initial reaction stage.

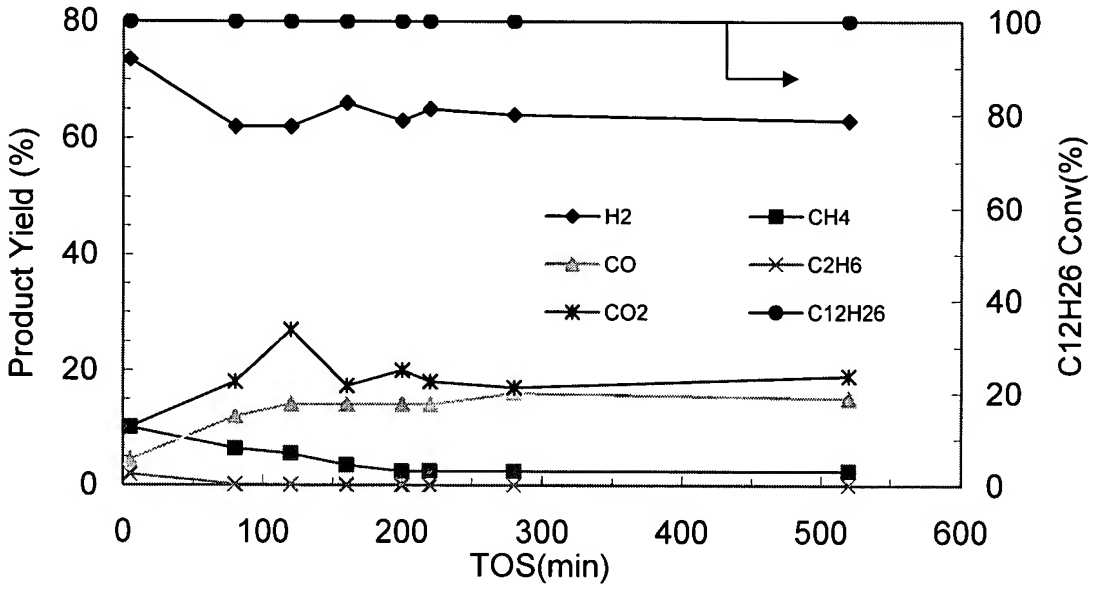


Figure 21 Experimental results from steam reforming of dodecane over a commercial catalyst G-91

Exhibit 11

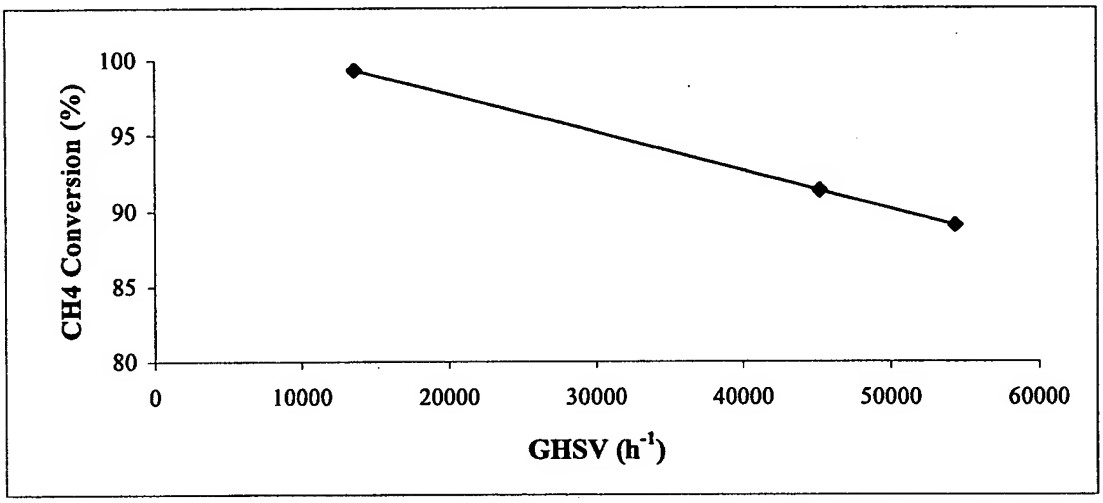


Figure 22. Steam Reforming of SGM-1 as a Function of Space Velocity (R1-C1 Catalyst, S/C=3, 700°C, atm)

Other catalysis were also tested. Figure 23 shows the test results with 4 other catalysts, containing either precious metal (P series) or non-precious metal (C series). The horizontal line in this figure represents the target metric for this reporting period (80% conversion). It can be seen that non-precious metal catalysts can meet this target at temperatures starting even as low as 600°C, while the precious metal catalysts can reach this target starting from 650°C.

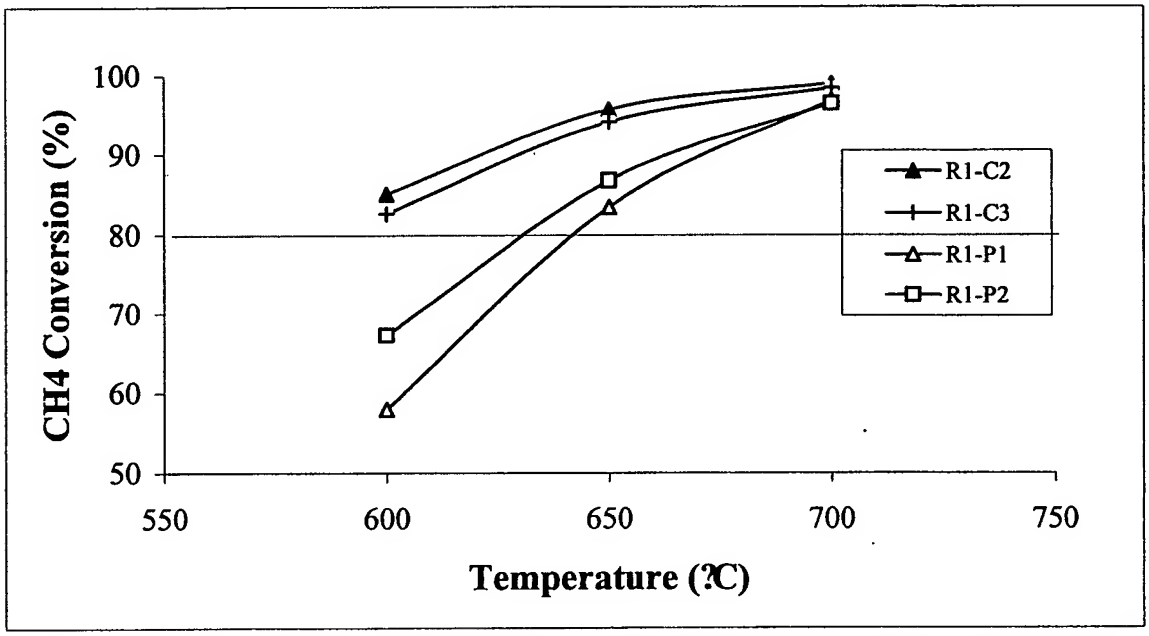


Figure 23. Steam Reforming of SGM-1 as a Function of Reaction Temperature (S/C=3, atm)

Exhibit 12